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**Determining Geotechnical and Hydrogeological
Parameters Using Downhole Geophysics
in the Canadian Plains**

Phase 1 Report

A REVIEW OF POTENTIAL APPLICATIONS

VOLUME I

April 1987

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on behalf of the

**Downhole Geophysics
joint venture research group**

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MICROMEDIA

EXECUTIVE SUMMARY

The Downhole Geophysics project resulted from the desire of several resource companies and geoscience consulting firms to improve the cost-to-data ratio of obtaining hydrogeological and geotechnical information for both coal and oil sands mining operations.

Proposals for joint industry and government research funding were prepared and submitted. The acceptance of these proposals for 50/50 industry/government funding by the Alberta and Canadian Governments resulted in the commencement of the project in November 1986. The project was divided into three phases, the results of the first Phase being reported here.

The objective of the first Phase is "to examine the current state of the art and the published literature concerning the use of downhole geophysics to obtain various geotechnical and hydrogeological parameters." This examination was conducted by various members of the project joint venture and consolidated into this report of the Phase 1 work.

The geotechnical and hydrogeological parameters of interest for the project were developed by the geotechnical and hydrogeological working committees. The work was then divided into six main areas to be addressed. These areas included:

- Literature search
- Review of geophysical instrumentation
- Review of geotechnical papers
- Review of hydrogeological papers
- Current research and developments
- Software for parameter determination

The literature search was based on an extensive list of keywords developed by the participants and the working committees with input from an external panel of experts. Several searches were required with various search strategies to generate a manageable citation list that provided reasonably complete coverage. In all over 1400 citations were produced from nine data bases.

Elimination of duplications and clearly irrelevant citations reduced this to over 430 citations.

This citation list was inspected by various participants and experts to produce a list of desired papers for detailed reviews. One hundred and thirty seven papers were obtained and reviewed by the project participants and authors.

Three main classes of geophysical instrumentation were identified along with four other measurement systems which, while not strictly geophysical, can be used for determining some of the parameters of interest to this study.

These seven groups of instrumentation include:

- | | |
|-------------|--|
| Electrical | - eleven methods of which six appear to have potential for further study |
| Nuclear | - three methods |
| Acoustic | - three methods |
| Caliper | - direct hole shape measurement |
| Temperature | - direct measurement of borehole fluid temperature |
| Flow | - direct measurement of fluid flow in the hole |
| Image | - both visual and acoustic images of the borehole walls. |

In the review of potential geotechnical applications, it is apparent that several of the desired geotechnical parameters can be determined from currently available geophysical logging and interpretation techniques. These include better use of dipmeter logs (three point micro resistivity) for structural interpretation and possibly joint set identification. Density, porosity and in some cases mineralogy can be obtained from the gamma-gamma, neutron and natural gamma logs respectively.

Acoustic methods such as transit time, vertical seismic profiling and cross-hole seismic logging have potential to provide information concerning density, dynamic elastic properties of rock, faults, fractures and lithological surfaces.

Radar's high penetrating power suggests that it will provide structural information between the boreholes. The actual penetration, however, is very dependent on the local rock resistivities. As well, the requirement for a resistivity contrast along the structural feature of interest means that radar's effectiveness will be very site specific.

The review of geophysical applications for the determination of hydrogeological parameters reveals that the petroleum industry is well advanced in this area. The determination of porosity from neutron logs and permeability from resistivity and natural gamma logs (Archie's formula) are widely accepted in the oil and gas industry. The reliability of these interpretations has yet to be confirmed in the shallow fresh water borehole environment found in coal and oil sand exploration.

Flowmeters and temperature probes are reported to be able to provide information on the distribution of permeability within the borehole and the location of aquifers. Other potential uses include seepage evaluation in tailings dykes and dewatering efficiency testing.

Water quality determinations have been made through correlation of total dissolved solids and water resistivity. Work has also been done using a small diameter induction probe for measuring changes in water quality over time.

Current research into geophysical instrumentation and methods reveals that there are a large number of groups working in this area. Several companies are improving and refining geophysical probes for better accuracy and smaller diameter holes. This includes combining several measurement systems into single probes to reduce the number of logging runs required.

Borehole systems for radar, VHF radio imaging, magnetic susceptibility and low frequency electromagnetics are being developed and tested with commercial products available in some cases.

Work is being conducted on the possibility of measuring several geophysical properties while the borehole is being drilled. Besides the mechanical properties, gamma and resistivity measurements are currently being attempted.

There are many software packages available for manipulating and displaying various geophysical logs. Only a few of these, however, have inbuilt interpretation techniques for determining any of the desired geotechnical or hydrogeological parameters. The reliability of these few inbuilt routines has not yet been demonstrated in the plains sedimentary environments commonly found in coal and oil sand exploration and mining. Software will need to be selected that allows the users to develop their own interpretation techniques. This will require as much flexibility in the analysis and display of the various logs as is possible to obtain.

This "state-of-the-art" review of the use of borehole geophysics shows that there are techniques available to determine some of the geotechnical and hydrogeological parameters of interest. The reliability and effectiveness of these techniques in the shallow, soft rock typical of the western Canadian coal and oil sand mining situations has not been fully evaluated or in some cases even attempted.

It is recommended that interpretation techniques to determine various parameters of interest be tried using one or two computer software packages. Data for this work should come from currently available geophysical and laboratory data. A recommendation on which additional geophysical log data needs to be collected for further work should be developed. The progress of ongoing research by other groups should continue to be monitored to enable adoption of the best and most current techniques in the determination of geotechnical and hydrogeological parameters.

PREFACE

This report reviews the literature and state of the art in the use of downhole geophysics to determine geotechnical and hydrogeological parameters. The results reported in the following chapters are based on the work completed as Phase 1 of the Downhole Geophysics Project undertaken as a joint industry/government research investigation. The project joint venture is funded by the following companies and organizations:

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The work plan organization, control and reporting was supervised by a Geotechnical Committee chaired by Mr. Geoff Jenkins of Manalta Coal and a Hydrogeological Committee chaired by Mr. Andrew Hickinbotham of TransAlta Utilities.

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DOWNHOLE GEOPHYSICS PROJECT

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1. INTRODUCTION

1.1 Project Formation

The Downhole Geophysics project resulted from the desire of several resource companies to reduce the cost of obtaining hydrogeological and geotechnical information required for both coal and oil sands mining operations.

Several of the participants were involved in a previous research project to evaluate the potential of using surface geophysics to aid in coal exploration. The success of this project provided the incentive to form a research project to explore various means of obtaining geotechnical and hydrogeological information from downhole geophysics. Discussions with potential participants in 1985 led to the formation of the Downhole Geophysics Joint Venture Research Project. Because of the participants' interest in both oil sands and coal mining, the project was developed to examine the potential of obtaining geotechnical and hydrogeological parameters in both coal and oilsands formations and overburden. The details of the project organization and management are described in Appendix 1.

Proposals for joint industry and government research funding were prepared and submitted in the spring of 1986 to the Alberta Office of Coal Research and Technology and to Supply and Services Canada to fund the coal and oil-sands portions of the work respectively on a 50/50 basis with the industry participants. Technical acceptance of the project by the funding agencies occurred in the summer of 1986 with detailed work commencing in November 1986 when financial approvals were completed.

1.2 Background

Mining companies and geoscience consulting firms aim to reduce costs, maintain high levels of safety and reduce the effects of the operation on the environment. In order to meet these objectives, mine planners require more geotechnical and hydrogeological information, which will enable them to predict highwall and spoil angles with greater confidence, reduce land disturbance,

predict and better handle disturbances to the local groundwater regime, assist in equipment selection and reclaim the mined out areas in a faster and more cost efficient manner.

The Alberta coal and oilsands deposits present a variety of geotechnical and hydrological problems as a result of their geological and geographical settings. They lie within poorly lithified clastic sediments that were deposited in deltaic, fluvial and estuarine environments during Jura-Cretaceous and younger times. The sediments are characterized by variations in lithology, both horizontally and vertically, over very short distances, so that it is difficult to correlate rock types, geotechnical characteristics, hydrogeological parameters, etc. without closely spaced drilling.

In addition to their stratigraphic complexity, the deposits have received varying degrees of tectonic deformation. The deposits of the Foothills and Mountain regions are strongly deformed, and are characterized by folds, a variety of types of faults, sheared zones, and joints. The Plains deposits (including oilsands) exhibit less faulting and little folding, but are jointed and in some areas have suffered glaciotectionic deformation, thereby contributing to their inherent weakness.

Pit slope stability, strip mine highwall stability, floor heave, floor trafficability and groundwater are major concerns in open-pit mining. Roof and floor conditions, stope dimensions, subsidence, groundwater and pillar strength are critical in underground mining.

The current methods of obtaining geotechnical information require time consuming and costly core drilling and laboratory testing. Obtaining hydrogeological parameters also requires expensive field testing such as packer tests and long term pumping tests.

Most of the resource companies in Alberta currently drill open holes and geophysically log them to obtain the lithological information required to do overall structural geology and to delineate the reserves. Minimum core drilling and laboratory testing are done to obtain geotechnical information because of the high cost involved. This forces the mine designer to evaluate designs based on very

sparse data. To account for localized changes in structural geology, rock strength and friction forces when the data are limited, the designer usually uses higher factors of safety and limited pit wall angle changes. This can result in higher strip ratios than necessary on one hand and localized wall problems on the other.

Similarly, obtaining hydrogeological information such as permeability and piezometric heads requires specialized field testing. This information affects both geotechnical design considerations as well as requirements for in-pit and surface water handling. The need to forecast the effects of mining on the groundwater table and quality are mandatory in obtaining environmental approvals for mining.

If the geophysical logs currently being recorded could be interpreted to obtain some or all of the required geotechnical or hydrogeological data, or new downhole geophysical tools or methods developed, the mine planners would have a better data base upon which to formulate the required design decisions. As a result of the additional information available from the same exploration dollars, the increased confidence in the parameters could reduce mining costs, improve safety and better predict the environmental impacts.

1.3 Objectives

1.3.1 Objectives of the Total Research Program

As outlined in the original proposals the objectives of the research program are to "... improve... and develop new techniques of using borehole geophysical data to determine geotechnical and hydrogeological characteristics of subsurface materials."

1.3.2 Objectives of Phase I (1986/1987)

The total project was divided into three phases. The objective of Phase I, conducted from November 1986 to March 1987, and reported here is "to examine the current state of the art and the published literature concerning the use of downhole geophysics to obtain various geotechnical and hydrogeological parameters."

The scope, objectives and methods of the subsequent phases will be modified to reflect the results and conclusions of the previous phases.

2. PROJECT APPROACH

2.1 Scope

The parameters which were considered in developing the detailed work plan and reviewing the information were selected by the Management, Geotechnical and Hydrogeological committees with help from external experts. These parameters are listed in Tables 1 and 2.

Table 1
Geotechnical Parameters

shear, tensile and compressive strengths
peak and residual cohesive strengths
angle of internal friction
modulus of elasticity
shear modulus
bulk modulus
Poisson's Ratio
confining stresses
lateral stress ratio
moisture content
density
strike and dip of structure, bedding and faults
ground temperature

Table 2
Hydrogeological Parameters

water table
pore pressure
aquifer and aquitard delination
fluid flow
permeability
transmissibility
porosity
saturation
specific yield
storage coefficient
fluid conductivity
gas/liquid ratio
water quality
fluid temperature

2.2 Work Plan

The work plan to meet the objective was developed jointly by the Geotechnical and Hydrogeological Committees. The project was broken up into various sections and stages because of the size of the project and the desire by some of the participants to conduct portions of the work themselves.

The first step was to define the keywords and conduct the literature searches. The keyword listing was compiled by the committees and circulated for revisions and additions. The revised master list of keywords was used to search various computerized data bases of publications.

The resulting list of citations was reviewed by the technical committees and the outside experts. From the citation list, relevant papers were identified and as many as possible were obtained for review by the geotechnical and hydrogeological working groups. This portion of the work is described in detail in Chapter 3.

The scientific papers collected were individually reviewed by the professional members of the working groups. The reviews were reported in a standard format and included the reviewer's opinion of the paper's importance to the project objectives (Appendix 5). The information obtained from the review of the papers was consolidated into Chapters 5 and 6.

A review was conducted to determine which geophysical equipment and interpretive software were the most capable of determining the geotechnical and hydrogeological parameters of interest. This information was obtained from commercial geophysical instrument manufacturers, geophysical service companies, users of geophysical services and researchers (see Appendices 3 and 4). Additional sources of information were revealed through the literature reviews. The results of this work are reported in Chapters 4 and 8.

Experts doing research in these areas were contacted to obtain as much information as possible about current, unpublished work. Naturally there was some reluctance to discuss work that had potential for commercial development. The researchers were identified during a review of the recent developments reported in the literature and contacts with the various geophysical service and instrumentation companies. The results of this investigation are described in Chapter 7.

Close contact between the working groups resulted in a beneficial cross flow of data, where information uncovered by one reviewer was useful to one of the other working groups.

Upon completion of the working groups' reviews and reports for the chapters, the summary of conclusions and recommendations was prepared. The result is a concise report on Phase I of the Downhole Geophysics Project.

A diagram of the work-plan logic is attached as Figure 1.

DOWNHOLE GEOPHYSICS PROJECT LOGIC DIAGRAM

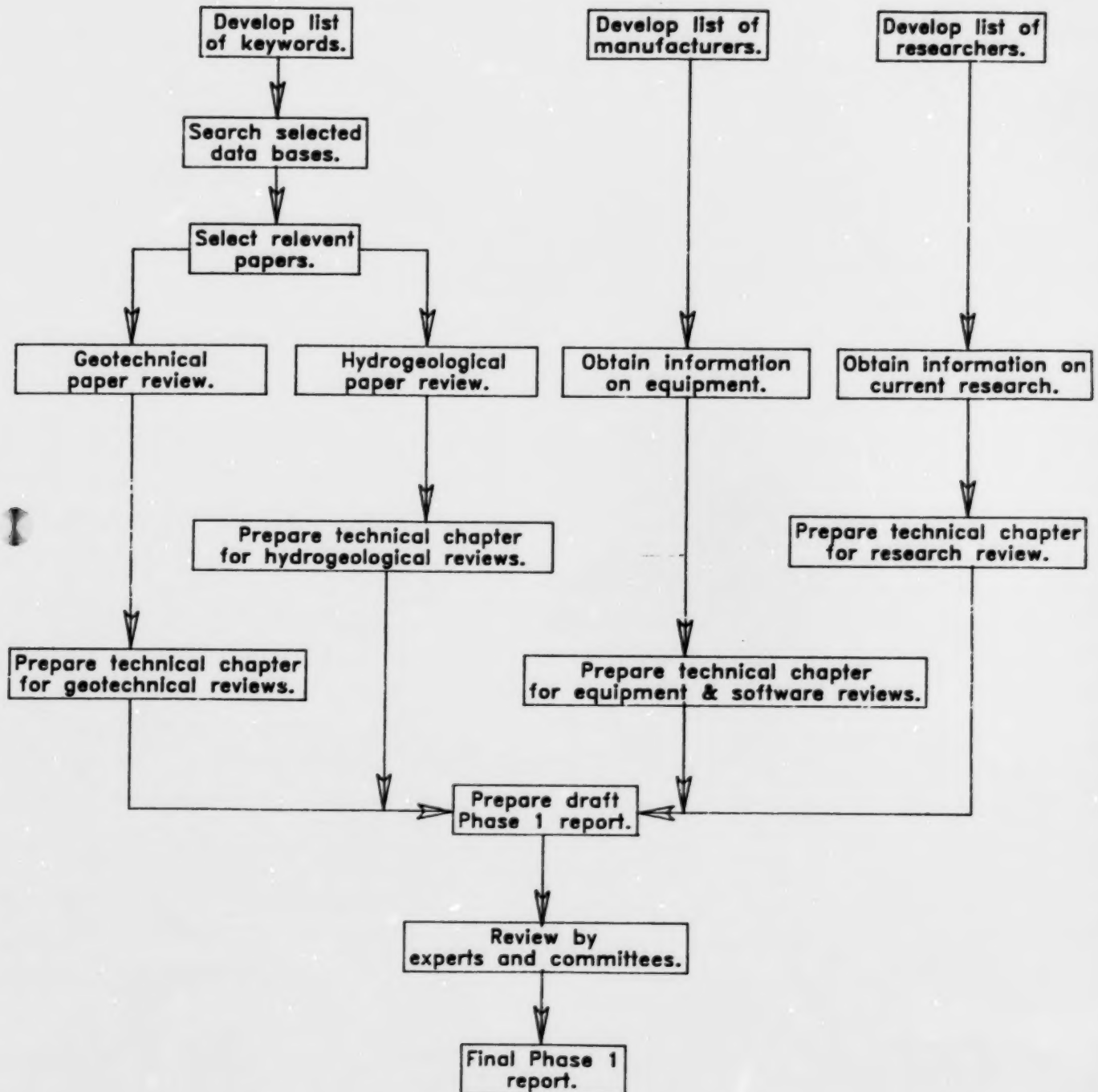


FIG 1: Phase 1 Work-Plan

3. LITERATURE SEARCH

3.1 Key Word List Development

A list of key words encompassing the entire hydrogeologic and geotechnical interest in geophysics was developed by the hydrogeological and geotechnical committees with assistance from many of the project participants.

The complete key word list is found in Appendix 2.

3.2 Computerized Database Search

3.2.1 Scope of Search

The emphasis of the computerized search was to target all of the most pertinent literature contained in the databases. A large number of citations were targeted and the titles were reviewed to make up a final bibliographic listing.

The following observations suggest a thorough search:

1. An extensive listing was generated using a thorough search strategy on the most pertinent databases including Georef, GeoMechanical Abstracts and Tulsa.
2. The databases searched overlapped with approximately 30% duplication of citations.
3. Many of the articles and nearly all of the authors in reference lists of various participants were found by the searches.

3.2.2 Search Products

A search strategy was formulated using the complete key word list so that all pertinent databases could be searched efficiently. The key words were arranged strategically so that the computerized listing generated from the relevant key words would include all pertinent literature but remain manageable in size.

The original search performed by Syncrude generated an unmanageably large listing. Therefore, key word "borehole" was dropped and the term "downhole" retained. This produced a manageable listing but was felt to be too restrictive causing pertinent papers to be overlooked. Therefore, the ARC again searched the databases using a revised strategy that incorporated both the borehole and downhole terms.

After comprehensive, manageable citation lists were generated, the lists were reviewed and clearly irrelevant references were eliminated. The number of relevant references, chosen from the total number of citations generated by searches on the various databases, are given below.

Database Searched	Total # of Citations	# of Pertinent Citations
Alberta Oil Sands Index (AOST)	12	2
Geoarchive File 58)	176	65
GeoMechanical Abstracts	161	59
Georef (File 89) Syncrude downhole only*	200	41
Georef ARC Downhole & Borehole	529	112
NTIS (file 6) downhole only	180	19
Tulsa	171	28
GPO Monthly Catalogue	<u>6</u>	<u>0</u>
TOTAL	1,435	326

*A search was also conducted on the World Patents Index which targeted 293 references. This listing, restricted by using only the term downhole, was used for the equipment survey.

3.2.3 Strategy of Computerized Search

The search was performed using key words that indexed many citations.

An example of the search strategy performed on the Tulsa database is outlined below.

Key Word	# of Citations by individual key word
Borehole	10968
Downhole	1304
Log	9992
Tool	10236
Device	9253
Instrument	26286
Hydrol	6594

[borehole
or
downhole] and [Tool
or
device
or
Instrument
or
Log] and [Hydrol] results in 45 citations

[12087] and [49503] and [6594] results in [45]

3.3 Abstract and Paper Selection

The pertinent citations from the computerized search were bound together with reference lists supplied by various participants to make up a bibliographic listing including over 430 citations. From this listing, articles and abstracts to be procured for review were chosen. Various participants and experts inspected the listing and chose citations they regarded to be pertinent to the downhole project. The selections were transmitted to the Alberta Research Council which administered the procurement of the papers or the abstracts of the paper or conference proceeding when the paper was not readily available. One hundred and thirty seven papers were reviewed by the participants and authors.

4. GEOPHYSICAL INSTRUMENTATION

4.1 Introduction

In this chapter the characteristics, capabilities and suitability of geophysical logging techniques are discussed. Commercially available equipment has been listed in Appendix 3.

Methods are assessed on the basis of the type of geotechnical or hydrogeological information that they can provide. Broadly speaking, borehole geophysical methods provide the following types of information relevant to this project:

- mapping fracture zones;
- the dip and strike of these fractures;
- salinity of borehole fluid;
- direction of fluid flow within boreholes;
- estimate of moisture content;
- estimates of the porosity;
- estimates of the dynamic moduli;
- estimate of the density;
- and mapping lithologies.

Most measurements are effective for a very limited distance, usually only a few centimetres, beyond the wall of the hole. However some methods extend to several metres or tens of metres. In addition, crosshole measurements when combined with the powerful tomographic processing methods, can provide interpretive sections between holes that may be up to, or more than, a few hundred metres apart.

Usually geophysical logging is carried out in uncased holes which are filled with water. However in the case of overburden investigations, the possibility of cased holes should also be considered. Any metallic casing is unacceptable for electrical logging. It is recommended that in this situation perforated PVC casing be used, and that it be allowed to stand long enough for the groundwater inside the casing to reach equilibrium with the groundwater in the

natural formation. Similar considerations would apply to thermal logging, however it should be noted that fairly lengthy equilibrium periods are needed for the thermal method. The nuclear methods are the least susceptible to the effects of casing. It is possible to conduct seismic logging through casing, however it is recommended that every situation be assessed individually. Caliper, television and acoustic televiewer logging is not possible in cased holes.

4.2 Electrical Methods

Eleven electrical methods are listed in Appendix 3. Of these, six appear to have potential for determining the desired parameter. These six methods are: single point resistance, normal resistivity (40 and 80 cm spacing), focussed normal resistivity, spontaneous potential, fluid resistivity, and radar.

In the single point resistance method the measured parameter is essentially the contact resistance of a moving downhole electrode. This log provides qualitative information and has been found useful for locating fracture zones and for giving some indication of the fluid conductivity and therefore the salinity of the borehole fluid. The normal resistivity logs, having a different working configuration than the single-point resistance logs, provide quantitative results. Resistivity being an intrinsic property of earth material and its saturating fluids can also be used to map changes in lithology. The focussed resistivity is a specialized variety of resistivity log which has a greater penetration into the wall rock, and a greater capability to resolve thin beds. The usefulness of spontaneous potential logs is questionable but can be included in the package because it usually forms an adjunct to the resistivity logs. Fluid resistivity logs, which measure the resistivity of the borehole fluid, have been found useful for locating the interface between fresh and saline water (Soonawala, 1983). This can indirectly indicate the points where groundwater either flows into or out of a hole. Similar information can also be provided by high-resolution temperature logs.

A dipmeter is a variation of focussed resistivity logs. The dip measurements are made by correlating the log responses from three or four micro resistivity pads equally spaced about the long axis of the probe. The probe also includes borehole orientation devices to enable calculation of the true dip and

strike of the various contacts in the borehole.

The above-noted electrical tools (except radar) are readily available commercially. Usually the resistivity, single point resistance and spontaneous potential probes are included in one tool, while the fluid resistivity is packaged with the temperature sensor.

Downhole radar is still in the development stages, and equipment is not as readily available on a commercial basis. It is a powerful technique that can sense to at least several tens of metres beyond the hole. It can be particularly useful when the requirement is to detect fractures that do not intersect the hole. Computerized data acquisition and data processing are necessary for borehole radar surveys. Tomographic interpretation has recently been applied to crosshole radar data (Olsson et al., 1986).

4.3 Nuclear Methods

The natural gamma, density (gamma-gamma) and porosity (neutron) methods are considered here.

Natural Gamma: The natural gamma logs can be very useful in differentiating between different lithological units, since these units often have characteristic and distinct potassium, uranium and thorium content. This method can occasionally be used to detect fractures in a borehole. In the spectral gamma method, it is possible to get an estimate of the quantity of individual radio active elements, the major ones being potassium-40, uranium-235 and -238 and thorium - 232. A suitably large sensor should be obtained if spectral gamma logging is to be successful.

Density: The gamma-gamma density tool is used for determination of material density. This tool measures the backscatter of gamma radiation from a source in the tool. The amount of backscatter is directly related to electron density which for most geologic structures is proportional to the material density. Careful calibration of the tool and caliper information for the borehole is required for reliable evaluation of formation densities.

Porosity: Porosity (neutron-neutron) logs indicate the amount of moisture and therefore porosity assuming full saturation in the rock in the wall of a borehole. They are also good indicators of fracture zones because there usually is an accumulation of water in fractures. However it is possible that concentrations of certain minerals may also cause a response on these logs. It has been reported that a good correlation also exists between the neutron-neutron log response and the point-load strength of rock (Elkington et al., 1982).

4.4 Acoustic Methods

Acoustic methods are usually applied only in consolidated rocks and require fluid-filled boreholes.

Sonic: In this method the transit time (and thus the velocity) and amplitudes of compressional (P) and shear (S) waves are measured. In the simpler type of equipment, which is commonly available commercially, only the first arrivals are detected and this precludes the detection of shear waves. This tool is useful for detecting fracture zones, porosity and rock type. In the more advanced type of sonic logging, the full waveform is recorded at each sampling point in the hole. The P and S wave velocities, in combination with density data, can be used to calculate the dynamic moduli that can provide an indication of the strength of the rock. Paillet and Hess (1986) have provided examples of how the frequency spectrum of acoustic waves can vary with the rock type. A critical consideration is the separation between the transmitter and the receivers. Generally, larger separations would provide data that are more representative of the formation being investigated.

Tube-Waves: Tube-wave logging (Huang and Hunter, 1984) is a surface to downhole seismic method, that also can be referred to as vertical seismic profiling (VSP). It can be used for fracture zone detection, and a correlation has been noted between tube-wave amplitudes and hydraulic conductivity of fractures. The tube-wave logs can also be generated from full waveform logs by appropriate processes (Keys, 1987).

Crosshole Seismic: The crosshole seismic technique, when used with tomographic data processing, can produce a map of the fracture zones in the section between two holes (Wong et al.,1987). In good quality rock the distance between boreholes can be up to a couple of hundred metres, but it should be noted that this range is highly dependent on the quality of the rock. Sophisticated software packages are available for the various tomographic processes which have been developed.

Crosshole seismic surveys can also be carried out using in-hole shear hammer sources. P and S wave analysis can be carried out to calculate the dynamic moduli of the intervening rock mass. Tomographic inversion is not possible with the limited number of ray-paths that can be generated in such a system.

4.5 Caliper Logging

Caliper logging is an essential component of any logging program. In this tool, mechanical arms are used to measure the diameter of a borehole. Caliper information has the following uses: fracture zones can be mapped; borehole diameter is used to correct and calibrate other tools; and some idea of the lithology can be obtained since the hole diameter in softer rocks tends to be larger than in more competent rocks.

4.6 Thermal and Flow Logging

Thermal logging has been used to determine the points where water flows into or out of a hole, and the direction of flow. Therefore, it can be of use in hydrogeological investigations. The natural thermal gradient can also be determined with this method. Drury (1984) has provided an analysis describing how fluid flow directions can be determined from thermal logging.

The heat-pulse flowmeter has been used to determine very slow-velocity movement of borehole fluid (Hess, 1986). It is claimed that velocities that can be determined are an order of magnitude lower than those detectable by impeller type flowmeters. The impulse or impeller type flowmeter serves the same purpose as the heat-pulse flowmeter but, as noted earlier, is far less sensitive.

4.7 Television and Acoustic Televiwer

The television and acoustic televiwer logs are used to locate fracture zones along boreholes with an accuracy of the order of millimetres. By analyzing the shape of the image, the dip and strike of the structure and fractures can be calculated (Lau, 1980). Therefore, these methods can be useful for detailed geotechnical studies, where the dip and strike information can be useful for interpolating fracture zones in rock between boreholes. The working principles of the two methods are different, but similar results are obtained. In order to use the television technique, it is necessary to have clear borehole fluid, and preferably light-coloured rocks.

5. REVIEW OF GEOTECHNICAL APPLICATIONS

5.1 Purpose of Review

This chapter summarizes selected papers which focus on geotechnical applications of geophysical logs. The selected papers concentrate on those studies which had positive results.

Of particular interest are tool developments which have taken place in the metallic mineral sector and the oil and gas sector and which have not been applied in coal or oil sands. Both qualitative as well as quantitative studies have been included in the review.

A one page summary form for each reviewed paper is included in the report appendices.

5.2 Geotechnical Parameters and Investigation Methods

5.2.1 Geotechnical Parameters of Interest

Geotechnical parameters required in the design of mine and tailings facilities are listed in Table 1 (Section 2.1).

This review has identified a number of borehole geophysical techniques which have been utilized to measure some of these parameters.

5.2.2 Investigation Methods

The general categories of geotechnical investigation methods are illustrated in the flow chart in Figure 2. The flow chart places borehole geophysics in its proper perspective, both in its currently accepted application and potential use. In evaluating and eventually choosing any given geophysical method, the technical merits and cost effectiveness of the method must be evaluated. In addition, the suite of methods which are eventually selected for testing should be done so that they are complementary and consistent with each other as well as the standard in-situ geotechnical tests.

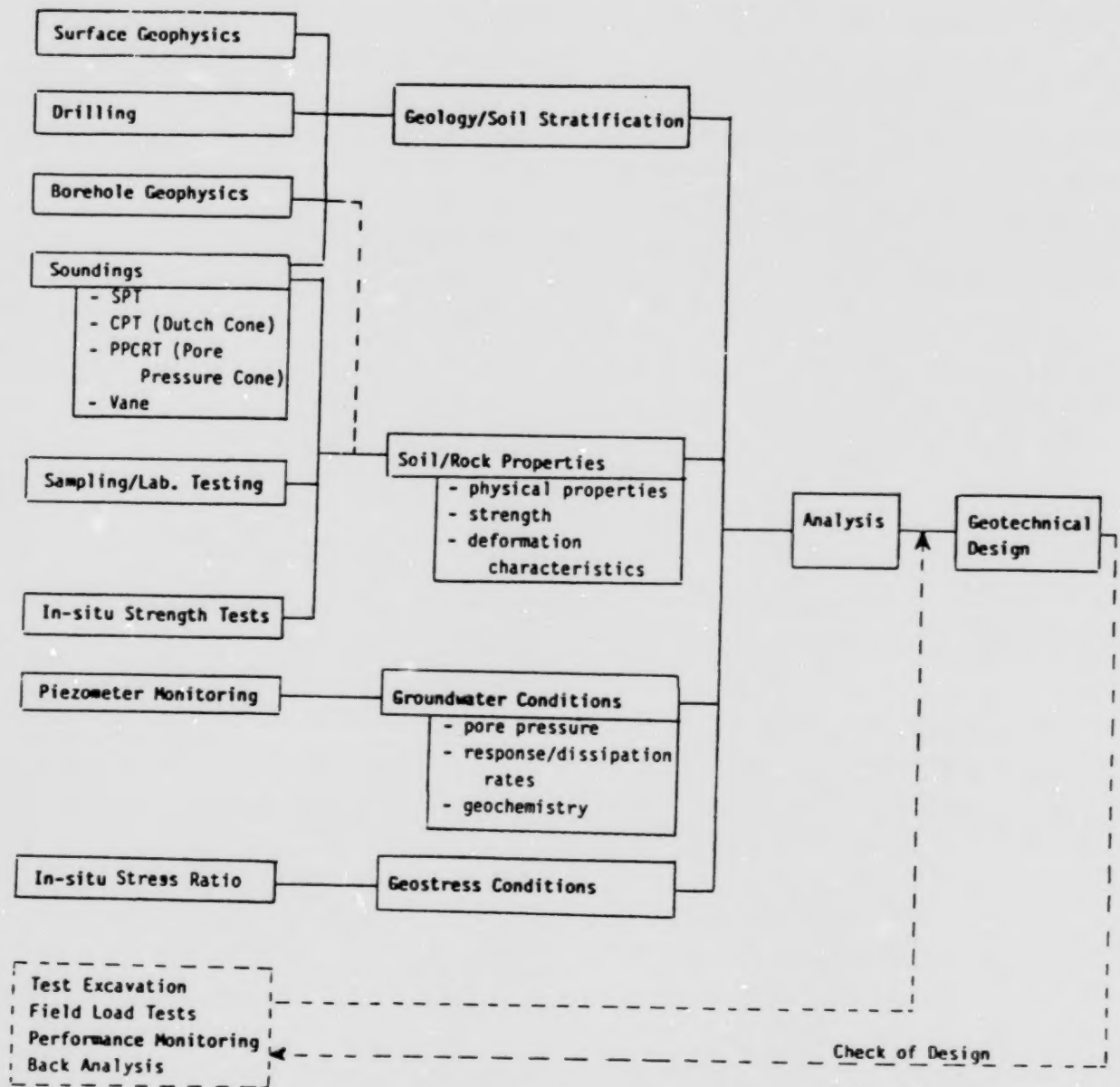


Figure 2 : General Geotechnical Investigation Methods and Objectives.

5.2.3 Evaluation of Methods

As recently mentioned by Tavenas, (1987) in-situ test procedures, should meet the following criteria:

- must be reproducible,
- calibrated against other tests,
- calibrated against performance.

Additional desirable qualities may be:

- simplicity,
- economy,
- good simulation of the problem.

These yardsticks have been utilized to evaluate the geophysical methods discussed in this chapter.

5.3 Summary of Relevant Papers

5.3.1 Borehole Televier

The borehole televier is an acoustic based probe which is available through at least two companies. This tool produces an image of the open wellbore to delineate such features as fractures, bedding planes and open porosity (Vuggy) conditions. The images which are recorded are the variable density representation of reflected acoustic waves. The reflected acoustic wave energy is dependent upon rock reflectance, wall roughness, wellbore fluid attenuation and hole geometry.

5.3.2 Testing and Calibration of Downhole Probes

One paper (Bernius, 1981) reports on a standard borehole test site in Ottawa and a second (Wenk & Dickenson, 1981) reports on a calibration facility in South Australia. The Ottawa site consists of four holes for which detailed geological logs and core are available to relate to physical property data acquired by logging. The Australian facility has been established to correlate gamma tool readings to equivalent U_3O_8 grades. Additional calibration facilities also exist in several U.S. centres.

A third paper (Mathew, no date) discusses high resolution core density logging ("Coran" instrument) which is based on gamma ray attenuation by core. It may be useful to compare field density results with data from this type of instrument in terms of cost effectiveness.

Development and use of standard calibration facilities will result in more uniform and universal logs and "absolute" property data.

5.3.3 Borehole Radar

At least two systems have reached the proto-type and testing stages. One system operates in the lower frequency range (< 50 MHz) while a second system (VHF) operates in the 30 to 300 MHz range. These systems have been tested in actual or simulated field conditions in both single and cross-hole configurations. Detection distances range from approximately 10 to 100 meters. The systems are dependent upon rock masses having a high resistivity and a large resistivity contrast to identify targets and may not be applicable in poorly consolidated sediments.

In a geotechnical application, the useful targets would be major fractures that offer a resistivity contrast for detection. This contrast may be caused by water saturation of the fracture.

5.3.4 Holography

Holography may be considered to be a geophysical procedure. A single paper (Bass et al., 1986) describes a new instrument for measuring the in-situ level of stress in boreholes. The instrument operates on the principle of locally relieving the stresses acting in a rock mass by drilling a small hole into the borehole wall and recording the resultant displacement field by holographic interferometry. A large diameter hole (> 30 cm) is required. The technique is experimental and as a result of the large hole diameter, expensive. For these reasons it may not be worthy of further consideration.

5.3.5 Dipmeter

The dipmeter has been widely applied in oil sand reserve evaluation and highwall stability over the past 10 years. Development of software and tests to compare dipmeter plots against oriented core data have taken this method to a high level of reliability. Bedding and local erosional surface features have been the primary strike/dip targets in these surveys. Resolutions as small as 5 mm have been reported (C. Brawner, 1987).

Bedding dips and geologic structures are key parameters in open pit slope stability evaluations as well as in underground mine design. Consequently dipmeter logs should also be directly applicable to foothills and mountain coal deposits and to tailings foundation studies.

Several papers have been located which accent the interpretation procedures required to fully evaluate dipmeter plots. One paper by Babcock, (1978), extends dipmeter interpretation procedures to identifying steeply dipping fractures intersected by a borehole. The method utilizes measurement of the azimuth of hole cross section elongation at zones of overbreak where the drill bit has encountered a fracture. Data are obtained from the caliper part of the dipmeter log. Satisfactory results have been obtained from numerous formations in Alberta. It can be particularly useful for identifying those fractures which do not have a significant resistivity contrast, and hence are not identified on the dipmeter plot.

5.3.6 Combination Probes

The complementary nature of some of the geophysical probes provides the basis for deriving rock mass characterization from integrated studies. In coal reserve evaluation studies the usual log suite includes the following probes: caliper, natural gamma, gamma-gamma (of various spacings for density), neutron - neutron or neutron - gamma, resistivity and sonic. In oil sand evaluation studies the usual log suite includes the following probes: caliper, natural gamma, gamma - gamma, neutron - neutron, resistivity or induction and SP. From these geophysical log suites, programs for both oil sands and coal have been developed to generate physical characterization data including density, porosity, saturation as well as oil

sand and coal quality parameters. However very little work appears to have been done to obtain data at a similar level from the overburden materials associated with coal and oil sand deposits.

Geona Enterprises Ltd. of Calgary has developed a statistically based computer system of log analysis and detailed reservoir mapping for heavy oil and oil sand applications, using the standard suite of logs. The system produces measurements of lithofacies gradation from clean clay rich shale to clean coarse sand. The data from all geophysical logs is systematically combined to produce the lithological discriminations. Currently proven and potential physical parameters that can be derived from this method of log analysis include: moisture content, including adsorbed water, gas content, degree and type of cementation, grain size distribution, clay mineralogy and plasticity. Since the system is statistical it requires a large data base.

A paper by Dyck and Young, (1985), urges that rock characterization for a variety of purposes including geotechnical properties, should be pursued by combining geotomography procedures using magnetic, electromagnetic and seismic measurements.

5.3.7 Sonic, Tube Wave (VSP), Acoustic and Geotomographic Methods

A large number of papers characterize rock and soil properties from measurement of compressional and shear wave propagation behaviour. These waveform borehole methods may be broadly categorized as:

- a) Conventional borehole acoustic transit-time logging;
- b) Borehole acoustic - refraction waveform logging;
- c) Acoustic borehole televiewer imaging of the borehole wall;
- d) Surface to borehole seismic investigations tube waves (VSP) with very long seismic wave lengths;
- e) Cross-hole seismic logging.

Conventional acoustic-logging systems use frequencies of 10 to 25 KHz and source-receiver spacings of 0.3 to several meters to measure compressional velocity of material around the borehole. Some systems will also provide S-wave travel times.

Waveform logging techniques involve the digital recording of the entire acoustic pressure signal received by a conventional acoustic logging probe. The acoustic waveform has been used to determine the in-situ properties of fractured rocks and other geohydraulic parameters.

Tube-wave (Vertical Seismic Profiling) operates with surface shot points and down hole compressional wave recording. Positioning and orientation of the shot point allow three dimensional rock characterization, including acoustic detectable features not intersected by the borehole.

One abstract presents the status of an acoustic logging tool known as "EVA" (Arditty, et al.). The tool, together with a data support system, collects and processes data to provide P, S and Stonely waves, velocity logs, amplitude logs and period logs. It also establishes the different elastic parameters. Further iso-offset section and data processing results in lithology identification, casing cementation requirements, damage zone identification and fine lithologic changes. It may also be used to estimate fracture permeabilities but the paper abstract available does not provide details on the method.

Cross-hole seismic logging allows the determination of rock/soil properties between boreholes and has formed the primary data source for geotomography. This procedure has been applied to identification of fracture zones, density distribution and mapping lithological contact surfaces.

Generally, the foregoing acoustic tools have been used for directly deriving dynamic elastic properties including: Young's modulus, shear modulus, bulk modulus, Lamé's constant and Poisson's ratio. In addition the methods have been employed to identify major fractures, fracture zones, and lithological surfaces. Various studies (New, 1986; Poule, 1984; Paillet, 1985; Elkington et al., 1982; and others) have been done to illustrate the direct correlation of

geotechnical properties to sonic/seismic data. Geotechnical factors examined include such parameters as rock quality designation (RQD), bucketwheel diggability, unconfined compressive strength and porosity.

In summary, adequate evidence exists to show that sonic property data including wave velocities, attenuation factors and full wave form characteristics may be used to derive relevant geotechnical data for mine and tailings planning purposes.

5.3.8 Gravity Probes

Several papers describe the application of gravimeter surveys to mining. The borehole gravimeter has an investigation range of several hundred meters and this is its singular advantage over most other borehole methods. However, the primary mining application is its ability to identify relatively large bodies which possess a measurable density difference (contrast) in comparison to the surrounding rock. Specific geotechnical data from gravity surveys have not been presented in the literature reviewed.

5.3.9 Neutron - Neutron Probes

This probe comprises a fast neutron source and a slow neutron detector. Published work (Halker et al., 1982) by the U.K. National Coal Board has demonstrated a close correlation between a Fracture Index derived from core logging and the neutron log. The Fracture Index was also correlated to the sonic log derived data and a caliper log. However, of the three logs, the neutron - neutron logs consistently showed the best correlation with the Fracture Index when water saturation or clay filled. Reasonable results were also obtained in generating compressive strength correlations with a related parameter, the Hydrogen Index. From the correlation a synthetic (continuous) unconfined compressive strength log was derived. A similar exercise was repeated in another paper to show the relationship between Neutron -Neutron log responses and point load strength data. Here again, the correlation was superior to other commonly used logs including the sonic log data.

5.3.10 Gamma - Gamma Density

The gamma - gamma density probe has a long history of use in both oil sands and coal logging suites. This tool provides bulk density values which are absolute values when the tool is properly calibrated. The results however are sensitive to borehole conditions, particularly the borehole diameter, and must be corrected for diameter variations. Most logging systems can make this correction automatically over a small range of diameters. Recent geotechnical applications include the use of measured density values to estimate liquefaction potential in foundation areas where saturated loose sands are known to exist. In one study the method of Seed and Idriss (1971) using relative densities derived from log data are compared favourably to standard penetration test (SPT) data. A similar favorable comparison was made by calculating void ratios from log data and estimating liquefaction potential using the critical void ratio concept (Wilder et al., 1983). The geophysical log method has the advantage of identifying thin zones of low density. However, it suffers from its dependence on borehole conditions and shallow penetration (ie. small sampling radius which may correspond to the zone of borehole disturbance).

A second procedure, developed in Holland (Nieuwenhuis & Ruijgrok, 1978) utilizes separate gamma source and detector sets in separate boreholes, (i.e. a cross-hole gamma system). The purpose of the method is to provide densities for layers not less than 15 cm. The equipment and procedure were designed to provide reliable in-situ densities for a variety of structures such as hydraulic fill, tailings compacted fill and densified hydraulic fill. The disadvantages of the method include dependence upon accurate positioning and orientation of the adjacent boreholes and borehole disturbance.

A third application (Timofeev et al., 1972) of gamma - gamma density logging demonstrates a correlation between log determined densities and rock bolt efficiency. Correlations of strain changes and pressure changes to density logs were also completed in this study.

5.4 Results

Based on the literature search, those methods which offer the best promise for application to either coal or oil sand mining operations or both include:

a) Acoustic Televiewer

This procedure offers a complete rendition of the acoustic reflectivity of the borehole wall and has potential application in fracture identification and providing an alternate method for providing detailed logs where core recoveries are unsatisfactory. The method merits further study.

b) Pulse Radar

The radar method would appear to have some application where fracture identification is merited. Penetration distances are quite variable and highly dependent on local resistivities. Given the resistivity contrast, the radar method may also have an application in defining other structural features that are relevant to geotechnical design e.g. overburden glaciotectionic structures.

c) Dipmeter

The dipmeter survey has direct application in slope stability evaluations and slope design for both coal and oil sand mining. Moreover, the examination of the application of this method to coal reserve evaluation, especially foothills and mountain coals, is definitely warranted. Babcock's method also appears to have merit for identification of fractures and fracture patterns.

d) Combination Probes

Geophysical probes in various combinations offer promise of providing useable data to define such geotechnical parameters as grain size, moisture, porosity, and plasticity. The best avenues for further study are software development and correlation analyses.

e) Sonic and Seismic

Geotomography to identify geologic structure and other properties such as in-situ density merits further study for overburden evaluation and tailings investigations. Methods for computing elastic parameters are quite well established in the literature particularly from conventional sonic borehole probe data.

f) Neutron - Neutron

The neutron - neutron log has seen successful application in British coal fields as a correlatable tool with point load test data and unconfined compression data. Further investigation to ascertain its possible application in Canadian coal and oil sand evaluation should be explored.

g) Gamma - Gamma

Cross-borehole tests to measure in-situ densities very accurately have had some measure of success in Europe. Application of this method to tailings liquifaction studies has distinct possibilities. Further study should be considered.

5.5 Conclusions

The relative importance of various geotechnical parameters depends on site specific conditions and the type of mine or facility likely to be designed. Generally, the parameters which are of greatest interest include density, moisture, porosity, saturation, shear strengths (effective and undrained) and structural features. Interpretation of structural features is also very important.

The available literature demonstrates that several borehole geophysical probes and methods as discussed have been sufficiently well developed to warrant testing in the coal and/or oil sand environment in a systematic manner.

6. REVIEW OF HYDROGEOLOGICAL APPLICATIONS

6.1 Introduction

The hydrogeological component of this project is focussed on the application of downhole geophysics to the determination or potential determination of major hydrogeologic parameters. The following major parameters have been identified, and in descending order of importance are:

- (1) permeability
- (2) pressure head or pore pressure
- (3) porosity, storativity (confined aquifers) and specific yield (unconfined aquifer)
- (4) moisture content and water quality in the unsaturated zone

These parameters apply in unconsolidated and consolidated sediments.

The papers identified and selected in the literature search plus any additional references in the hands of the authors were reviewed. Many of the most recent papers are related to unique site conditions and information needs particularly for igneous-metamorphic geological settings. Whether or not these techniques can be extrapolated to the sedimentary environment with success has not been examined.

6.2 Current Uses

6.2.1 Borehole Damage and Drilling Effects

Nearly all log interpretation in the petroleum industry is conducted under open hole conditions. As a result, tool design and log interpretation procedures are geared toward removing or correcting borehole effects due to mud invasion and the drilling process. To maintain hole stability, it is "mudded up" to ensure that the weight of the drilling fluid column is greater than the pressure of the fluids in the formation. While this achieves mechanical stability of the hole by applying a backpressure to the formation, it also forces the drilling fluid to enter the formation.

In shallow fresh water environments, it is questionable how much mud invasion actually takes place. Alger (1966) contends that mud invasion is limited because the porosity is high and the pressure differential between borehole and formation fluids is relatively low. In most cases, therefore, the resistivity value from a 41 cm short normal electric curve is very close to the true formation resistivity. However, Dyck et al. (1972) has observed that invasion of drilling mud does occur in shallow, fresh water environments sufficiently to cause errors in the 41 cm normal resistivity log. A small diameter induction probe recently developed by Geonics Ltd. may prove useful in accurately measuring conductivity beyond the mud invaded zone.

If the 41 cm short normal electric log reflects true formation resistivity because of limited invasion as stated by Alger (1966), then the effects of mud resistivity are insignificant. The log interpretation procedure is then simplified where mud rotary drilling is the predominant method.

The aspects of mud properties and formation damage in shallow groundwater wells was extensively reviewed by Haines & Emerson (1972). In contrast to the specifically prepared and often exotic mud mixtures employed in petroleum drilling, that used in water well drilling often consists of a simple mixture of bentonite and locally available water. The formation of a mud cake is perhaps the most important function of the mud in drilling technology. The mud cake both stabilizes the borehole walls and reduces fluid loss to the formation. The thickness of the mud cake depends primarily on the rate of deposition of solids from the mud, the rate of erosion by the circulating mud, the strength of the mud cake, the temperature and the differential pressure between mud column and formation.

The use of deep penetrating side wall tools in the coal and oil sands formations significantly reduces any effects of mud caking or invasion.

6.2.2 Permeability (primary and secondary)

From Resistivity Logs

The determination of intergranular permeability is based on extensive log experience developed within the petroleum industry. The groundwater industry has generally adopted, without modification, the well documented Archie formula, $F = R_o/R_w$ where F is the formation factor, R_o is the saturated resistivity of the formation and R_w is the resistivity of the formation pore water. The Archie formula, derived for hydrocarbon applications, is only applicable in saline water environments where current flow is through the formation fluid. Under this circumstance F is a constant for each lithologic unit. In fresh water environments, most water bearing aquifers contain some clay which results in both a surface conduction and pore fluid current flow. The net effect is that the formation factor is no longer a constant but rather varies with R_w (Alger, 1966; Worthington, 1975).

A number of approaches have been developed to determine either F or R_w . Jones & Buford (1951) solve the equation by determining F from laboratory studies and R_o from an electric log. Kwader (1982) determines R_w from a fluid resistivity log or from a knowledge of groundwater quality determined on near-by pumped wells. Another approach is to determine R_w by cross-plotting R_o versus porosity obtained from a neutron or density log. R_w can be measured directly in the borehole using a fluid resistivity tool. However, this approach necessitates developing the well to remove all foreign water and mud that accumulated during drilling. A fourth approach is to correct F or R_w by a parameter indicative of clay content. The ultimate objective being to determine F where a relationship between F and permeability is proven to exist (Croft, 1971; Kwader, 1982). F can also be determined from $F = a/\phi^m$ where a is usually 1 and the cementation exponent $m = 1.3$ to 2, depending on lithology. ϕ (porosity) can be obtained from neutron, gamma-gamma or acoustic velocity logs (Keys, 1987).

Because of the effects of surface conductance in fresh water environments, the outstanding problem in quantitative hydrogeological applications is the field determination of R_w . Worthington (1975) has identified the induced polarization method as a possible technique to define clay content and hence correct for surface conductance effects.

A quantitative assessment of the hydraulic conductivity of near surface materials at a dam site was developed by Schimschal (1981). He used hydraulic conductivity measurements calculated from pump tests, porosity measurements from core samples and water quality measurements from water samples to relate the hydraulic conductivity to the resistivity log. The formula:

$$\log R_o = \log R_w + \frac{m}{D} (A k^B - C)$$

was developed from the following equations.

$$N = A k^B \quad (1)$$

$$N = C - D \log \phi \quad (2)$$

$$R_o/R_w = \phi^{-m} \quad (3)$$

where N = neutron response, k = hydraulic, ϕ = porosity

m = cementation exponent, R_o = bulk resistivity,

R_w = pore fluid resistivity and A , B , C , D are constants.

Constants A and B are calculated from equation (1) by plotting k from pump tests against neutron log response. C and D are found from plotting porosity determined from core samples against neutron log response. R_w is determined from water samples and m is calculated from equation (3) by plotting ϕ against R_o .

There appears to have been significant progress made in the oil industry for defining log derived permeability. Examples include:

1. Dependence of "k" on water saturation which assumes that residual (is reducible) water saturation (S_w) is proportional to specific surface area. Timus (1968) tested the relationship on sandstone with the equation,

$$k = \frac{a \phi^b}{S_w^2}$$

2. Cheng (1986) has a modified version by incorporating a porosity correction factor F into the Timus equation. In his particular application the best calibration was obtained by the eg.,

$$k = 0.136 \frac{(\phi + F\phi)^{4.4}}{S_w^2} \quad (\text{Timus Equation})$$

and

$$k = C^2 \frac{(\phi/100)^6}{(S_w/100)^3} \quad (\text{Wylie - Rose Equation})$$

k = permeability

ϕ = effective porosity (%)

F = porosity correction factor (dimension not applicable)

S_w = irreducible water saturation (%)

a+c= fluid dependent constants

These relationships are unique for each site and the solution for the above formulae can only be trusted if these relationships are strong. In the sedimentary geology of the Alberta plains, these relationships may be nonexistent. However, the approach shown here may work for different and more complex suites of logs and warrants further investigation.

From Gamma Ray Logs

Kwader (1982) has demonstrated a correlation between the "average" natural gamma activity of a hydrogeological zone and its formation factor. This approach is based on the assumption that either only one type of clay is present throughout the sequence or that the clay ratio responsible for gamma activity is constant.

As early as 1963 (Patten & Bennett) had indicated an interrelationship between gamma radiation and formation factor. Sandstones of high porosity are indicated by low formation factors and low radiation intensities. Sandstones that are lower in porosity because of high clay content will be indicated by low formation factors and high radiation intensities. Sandstones that are lower in porosity because of other causes will be indicated by high formation factors and low radiation intensities. Therefore, it should be possible to estimate the relative effectiveness of sandstone aquifers by comparing their formation factor and gamma ray data. This concept is supported by Rabe (1957) and Gaur & Singh (1965). Rabe established a relationship between permeability and gamma radiation for clay bonded Cretaceous sands of the Denver-Julesburg Basin. The relationship is limited to clay bonded sands as calcareous or siliceous cementing materials, which reduce permeability, would not be expected to increase gamma radiation above the clay free line. Gaur & Singh established a permeability relationship with the area under the gamma curve for an Oligocene sand. Oil sand aquifers are incremental sands which may not necessarily have any clay minerals. Their permeability is a function of grain size distribution.

A linear response between gamma radiation and clay content was established by Heslop (1974), and Johnson & Linke (1977) successfully correlated cation exchange capacity (CEC) with gamma response for sandstones in the Mackenzie Delta. Wheatcraft et al. (1986) likewise propose the use of CEC data based on gamma response, not specifically for a permeability determination but rather to characterize sediments for pollutant attenuation.

The utilization of gamma radiation to quantify permeability seems to have met with both success and failure depending upon the types and amount of clay assemblage, and the degree of cementation other than clay bonding. Because the gamma log is a commonly run log, a good potential exists for its utilization in determining permeability directly under given geological conditions, or as a means to correct formation factor or R_w .

The corrections to the Archie equation for clay content assume a consistent geochemistry and content of the clay. This may not be a valid assumption for the Plains sedimentary geology. What is needed is a detailed model of radioactive isotope content of the various clays. Hydrogeologic investigations

using resistivity logs and Archie's equation will be at best a purely empirical correlation. The model on which Archie's law was developed involves Poiseuille's flow in granular medium and is not valid for the geochemical structure of clay materials.

Gamma spectral logging or spectroscopy of neutron-induced γ (Hearst and Nelson, 1985) can provide qualitative information of the types of clays or minerals which emit γ -rays. The qualitative spectral signature for each type of clay and mineral must be identified to allow the calibrated tool to diagnose materials encountered in the borehole. A quantitative analysis of the materials is more difficult using this technique.

From Flowmeters

Development of geothermal reservoirs and site investigations related to radioactive waste disposal has resulted in a concerted effort to use flowmeters to measure water flow (Schimschal, 1981; Syms, 1980, 1982; Hess, 1982, 1984). The major thrust in the development of this technique has occurred within moderately deep test holes within an igneous-metamorphic geologic setting where resistivity exceeds thousands of ohm-meters and is often difficult to interpret (Keys, 1979). Flowmeter determination of permeability was developed as an alternative to the calculation of formation factor from electric logs.

Flowmeter surveys are run either within cased holes which have been perforated or screened or within open holes requiring a correction for borehole roughness with a caliper log. Because of the depth of hole associated with geothermal reservoirs and radioactive waste disposal sitings, a multiaquifer setting with internal flow is common. However, this is not always the case for shallow holes within the sedimentary environment. Within the igneous-metamorphic geologic setting, the holes are normally in good quality rock that does not require dense drilling fluids to maintain the opening and therefore mud invasion is not a problem. Within sedimentary environments, where holes are often drilled with mud because of hole stability problems, there is a need to flush and develop the hole prior to running a flowmeter survey.

In shallow sedimentary environments, there is rarely any significant hydraulic differential between the borehole and formation fluid.

Therefore, effective flowmeter results can not be expected from measurements of only natural vertical flow in a borehole whose water level is at equilibrium (Manabe et al., 1983). That is, internal flow or "thieving" must be occurring in order for the flowmeter to respond. An effective analysis of water motion can, therefore, only be accomplished by changing the water level in the borehole through a pump-in or pump-out test in order to induce hydrodynamic flow.

The distribution of permeability within a borehole can be analyzed in one day using a flowmeter. Flowmeters can be added to any logger at a relatively low cost and they are standard with many commercial logging companies. A heat pulse horizontal flowmeter capable of measuring seepage rates between 0.02 and 3m/day (0.1 and 10 ft/day) was tested in the laboratory (Melville et al. 1985). Very small channelization around slotted pipe and hydraulic conductivity contrasts can invalidate instrument response; therefore wells must be constructed and probes placed with great care.

An experiment comparing flowmeter analysis to tracer travel time and wellbore dilution is currently underway near Mobile, Alabama. The results from this study will indicate effectiveness of the flowmeter and provide suggestions for field procedures.

Other applications of flowmeters could include:

1. Constructing flow nets for tailings dyke seepage evaluation for environmental monitoring or filter performance.
2. Definition of barriers to water flow in groundwater modelling.
3. Dewatering/depressurisation efficiency measurement.

6.2.3 Pressure Head/Pore Pressure

Manabe et al. (1983) appears to be the only paper which addresses the issue of water head distribution for multi-permeable zones within a single borehole. Their method is based upon use of the flowmeter in conjunction with pump-in or pump-out tests. It is questionable whether or not this approach would have universal application to exploration drilling programs in coal or oil sands.

6.2.4 Porosity/Storativity/Specific Yield

Within the petroleum industry, porosity has traditionally been derived from the porosity suite of logs - neutron, density and sonic, with neutron and density generating a total porosity value. Porosity can be calculated directly from the density log with a knowledge of grain density and fluid density. Neutron logs, on the other hand, are calibrated directly in limestone porosity units or must be calibrated through core or laboratory studies in other rock types.

Porosity is very important to calculating hydrocarbon saturation in the petroleum industry. In groundwater studies, determination of porosity is not as important, because the variations in porosity are usually small for fresh water aquifers. A specific yield of 0.2 for water table aquifers and a storativity of 5.0×10^{-4} for confined aquifers are reasonable estimates. The influence of grain size and its direct relationship with permeability is of far greater importance.

In addition to the standard petroleum industry porosity logs, other approaches at defining water content within igneous-metamorphic geologic settings have been attempted. These are the electromagnetic propagation (EMP) method for determining water saturation in low porosity rocks and the nuclear magnetic resonance (NMR) method for distinguishing between bound and free water associated with clays and hydrothermal alteration products (Nelson, 1982). Tools using these methods are not readily available.

Secondary porosity can not be easily measured. To date, only the flowmeter appears to have been successful (Tate et al., 1970). Plumb et al. (1985) have attempted a qualitative indication of relative fracture permeability based on attenuation of Stoneley waves. Nelson (1982) commented that reliable determinations of permeability continue to be an elusive goal.

Indirect measures of flow can be obtained from fluid conductivity and temperature logs. Edmonds et al. (1976) used these logs to determine the source of water from water wells by tracing changes in fluid conductivity and temperature to induced flow from a river. Intervals of high secondary porosity can be identified by cross plotting neutron and acoustic velocity logs (Keys, 1986).

6.2.5 Water Quality

Alger (1966), Emerson & Haines (1974) and Kwader (1982, 1984) and others have demonstrated a strong correlation between total dissolved solids (TDS) and water resistivity R_w .

Kwader (1985) measures water quality with geophysical logs by establishing a relationship between water resistivity and ion concentration in the lab and obtaining the water resistivity from cross plots of bulk resistivity and porosity. Again, this method will not work unless a good relationship exists between porosity and resistivity. In sedimentary geology environments, resistivity is likely to be influenced more by changes in clay content, clay geochemistry and lithology, than by changes in fluid resistivity adjusted for porosity.

The small diameter induction probe mentioned in section 6.2.1, appears useful for measuring changes in water quality of an aquifer over time. This tool may prove to be more useful in determining water quality than classical resistivity logs. Temperature and fluid conductivity logs can also indicate water quality and identify flow regimes and flow sources.

6.2.6 Degree of Saturation and Water Quality

Within the unsaturated zone, only the radiometric logs - neutron, density and gamma, have any potential to correlate with formation properties. Neutron logs can be calibrated to define porosity below the water table and moisture content above the water table. Hearst (1979) used neutron logs to establish moisture content profiles in partially saturated alluvial sediments. Carroll & Muller (1973) successfully determined water content, porosity and degree of saturation using only a knowledge of the formation resistivity and density in partially saturated alluvial sediments. Extensive work is being performed at the Nevada Test Site on calibration and correction of neutron logs for determining moisture content above the water table.

The small diameter induction probe (section 6.2.1) at present appears to be the only tool with potential of recording water quality in the unsaturated zone.

6.3 Summary and Conclusions

The literature review has indicated a number of new approaches in downhole geophysical logging techniques. Many of these techniques are specific to particular problems and geologic settings. New tools and methods such as the acoustic borehole televiewer, seismic waveform analysis, and acoustic soundings have already met with some success in the Plains surface mining environment and may become more widely used. Other methods such as nuclear magnetic resonance, electromagnetic induced polarization and microelectric scanning have had some success. The many cross plotting techniques used in conjunction with Archie's formula extract information from standard logs. Computer analysis, including such techniques as cross-plots, ratios, differences and statistical studies will often reveal relations that are not initially obvious between geophysical properties and hydrogeological parameters.

There is potential for greater use of the flowmeter. A major disadvantage lies in the need to flush the borehole. Great care must be exercised in well installation and probe placement for these instruments to work.

The conventional logging suite comprised of a resistivity, gamma, caliper, density and neutron log, appears to provide the best potential for in situ determination of hydrogeological parameters associated with the Plains sedimentary environments.

A suite of hydrologic logs including the small diameter induction log, temperature log and conductivity log may together provide information on flow and water quality and will also describe the borehole fluid which affects other logs.

7. CURRENT RESEARCH AND DEVELOPMENT

7.1 Research Groups

Leading researchers and organizations were contacted to review the current state-of-the-art with respect to borehole geophysics. It was recognized that this review would identify geophysical probes which had potential for use later in the project.

Discussions with program participants, some of the program reviewers and staff at the Geological Survey of Canada resulted in the preparation of an initial list of both researchers and organizations which are or may be working in the subject area. These researchers and organizations are presented in Appendix 4, A and B and include worldwide groups from the private, education and government sectors. Most of these groups were contacted in this initial survey.

7.2 Interview Method

The personnel and organizations listed in Appendix 4 were interviewed using a structured questionnaire. Information pertaining to potentially relevant borehole probes, performance data, other contact references and pertinent literature were requested.

7.3 Measured Parameters

In order to focus the search activity, a specific set of geotechnical and hydrogeological parameters were compiled. The parameters which are normally required in the design of mine and tailing facilities are listed in Tables 1 and 2 in Section 2.1. Those borehole geophysical methods which show promise in terms of their potential ability to deliver these key parameters to an acceptable level of accuracy are discussed in the following section. This section has been organized on a generic basis.

7.4 Geophysical Probes

7.4.1 Impulse Radar Methods

Two probes have been developed and tested primarily in hard rock applications with reasonable levels of success. One of these systems was developed in the U.S.A. by Sandia National Laboratories and has successfully identified fractures up to a distance of 12 meters. Applications in soft rock or unconsolidated materials have not been attempted. A second system has been developed by Boliden in Sweden. This system is a slim hole dual probe transmitter/receiver system operating with a cross-hole geometry and requires a relatively high background resistivity in order to be effective. It has been tested in hard rock applications only. In low conductivity material, a range of 100 meters has been attained in identifying rock interfaces. Weathered zones have been identified with this tool and water-filled fractures could also probably be identified.

A third system, (Collett, 1987) better than either the Swedish or American systems is the Ekko 3 system developed by A Cubed. The system measures dielectric contrasts and is claimed to have a penetration of up to $\frac{1}{2}$ km in granites. This is a surface prototype but the developers indicate that a borehole version would not be an expensive undertaking. Development time would be required. This apparatus is particularly sensitive to porosity and saturation/fluid conductivity changes. A borehole version may have an application in identifying water filled fractures.

7.4.2 Neutron - Neutron Probe

The National Coal Board in the U.K has developed a tool and correlation data for special applications to coal only for identifying the degree of fracturing. The tool is marketed by Robertson Research. This tool has the ability to measure relative levels of fracturing and to estimate powder factors to achieve optimum fragmentation for both coal and overburden (Young, 1987). This tool may have a particularly useful application in new coal basin development. It may also have an application in future oil sand areas where overburden formations containing cemented beds are prominent.

A second generation large diameter pulse neutron tool is under development at Dresser Atlas. The tool is being built with improved sources to provide better data than currently available tools. Identification of water inflow points and fluid ratios is also claimed. There has been a change in research workers and additional information was not available but this tool may be worthwhile testing for obtaining porosity and saturation data.

7.4.3 Gamma - Gamma Probe

The Commonwealth Scientific and Industrial Research Organization of Australia (Dr. M. Borsaru) replied to our query with a description of the SIROLOG system. This appears to be the most reliable ash identification system and may have an application in providing a better resolution of clay mineralogy than existing systems. This system is now commercially available through SIE Geosource.

7.4.4 Cross-Hole Seismic

Substantial progress has been made in the development of cross-hole seismic analysis and geotomography. Most of the available probes are slim line tools and have reached or passed the prototype stage. Most equipment will provide compressional wave velocity, shear wave velocity and full wave form data including amplitude and attenuation coefficients. These data can in turn be used to provide dynamic elastic properties, in-situ densities, fracture densities, fragmentation and powder factors. One of the major advantages of this type of system is its ability to sample large material volumes and avoid borehole disturbance problems especially in soft, unconsolidated or uncemented materials. Several applications exist for this type of equipment in mine overburden investigations to evaluate complex structures in three dimensions. Applications also exist in tailings dyke construction where the determination of in-situ densities and the mapping internal dyke structures is desirable. Research work is still underway in developing software for tomographic interpretation of multi-wavepath models.

In this survey, two researchers in Canada were contacted. Dr. P. Young at Queen's University and Dr. J. Wong of Jodex Ltd. appear to have made the most progress and further follow-up efforts to pursue potential applications are warranted.

7.4.5 Magnetic Susceptibility

Dr. W. Morris has developed a slim line probe (MAGLOG) for measuring the total magnetic field and bulk magnetic susceptibility. There is a slight possibility that this probe could be used to identify major zones of oxidation in those areas where appreciable quantities of magnetic minerals exist (iron oxides and sulphides). Active ground water flow zones could possibly be identified by correlation with areas where these minerals have been oxidized. The system has been tested in the oil sands.

Simplec (George Chapel) has also developed a magnetic susceptibility tool for slim holes.

7.4.6 Radio Imaging Method (RIM)

This method utilizes two slim hole probes in a transmitter-receiver configuration using radio wave signals. Various geometric combinations of receiver transmitter orientations are utilized to collect radio signal paths. The data are computer processed using an axial tomographic analysis package. This system will work in dry or wet boreholes in any orientation and is used to map coal seams, faults, washouts and major fractures. It has been used successfully in a number of boreholes in the U.S.A. and is now being tested in Australia. The system was developed by L. Stolarczyk and is available as a commercial logging service through Stolar. An oil sands application is not immediately foreseen but it may offer a method for 3-D mapping of basal aquifers especially if they contain saline or brackish water.

7.4.7 Borehole to Borehole Electromagnetic Systems

Researchers at the Southwest Research Institute have developed a cross-hole electromagnetic system for operation in vertical slim holes. The system operates

with a VHF pulse transmitter over a pulse spectrum of 0 to 500 MHz. It is claimed that the systems will provide data on cavity detection, geotechnical data (type not specified) and saturation levels. Borehole separations are small, in order of 5 to 20 meters. An interpretation program (software) is not available.

7.4.8 Multi-Probe System

The Southwest Research Institute has also developed a multi-probe system which is referred to as a "Geotechnical Probe System". This system includes seismic (P-wave), resistivity and electromagnetic (30 - 300 MHz) radar probes. They are combined to sound the surrounding rock mass to a radial distance of 15 meters from the borehole's axis. This combination probe is designed to identify lithologic as well as structural anomalies such as clay filled fractures, faults and unconformity surfaces. A data storage and plotting system is included to serve the system. The system has been tested in a hard rock environment only.

7.4.9 Heat Pulse Flowmeter

The USGS (Dr. F. Paillet) has recently developed a heat pulse flowmeter based on the principal of heat loss over repeated time increments. The equipment is in the prototype stage but should be available for testing in our proposed program, if desired. The specifications should be compared with similar flow meters (G.S.C., Geosource, OYO etc.) to assess the most suitable probe for our borehole conditions. Paillet also noted that the USGS has a large library of applications and software literature.

7.4.10 Acoustic Televiewers

J. Zemanke at Mobil Research developed an acoustic televiewer which is now available through Simplec Manufacturing. The acoustic televiewer provides a photo-like image of structural and textural features for the complete borehole wall. It is designed primarily to offer a complete rendition of fractures and bedding planes which intersect the borehole. This tool provides reliable fracture data in other geology and it is recommended that testing be considered in the plains sedimentary environment.

Schlumberger has a probe called the Borehole Televiewer which is also an acoustic logging tool. This probe produces an image of the well bore to delineate fractures, bedding planes, cavities and vugs in open holes. The tool is available in two diameters, 45mm and 95mm.

7.4.11 Dip Meter Probe

This probe is based on a three or four pad resistivity tool. It is not a new tool but over the past 10 years extensive work has been done by Schlumberger and others to develop additional software for interpreting bedding and other planar features. These tools are available in slim line versions from certain contractors.

7.4.12 Formation Microscanner Service

This tool was developed recently by Schlumberger and uses data from a dense array of electric sensors. These micro-electric scanning arrays are set on two caliper pads of a dipmeter tool. The system uses a new technique to make high resolution images of the formations. Two images oriented at right angles to each other are displayed using variable intensity gray scale. Major uses include: identifying fractures, recognizing secondary porosity and defining sedimentary structures. The tool is only available in a large diameter format and the minimum hole diameter is 160 mm. This tool appears to have potential uses in geotechnical investigations, especially in structurally complex areas.

7.4.13 Measurement While Drilling (MWD)

The oil and gas sector has seen the development of several systems to measure certain parameters at the bit while drilling. While most of the measured parameters are mechanical, two geophysical logs, gamma and resistivity, are included in these systems. The system measures and records mechanical and hydraulic drilling data and has been used to promote rig safety, drilling efficiency and on-the-spot preliminary formation evaluation.

7.4.14 Low Frequency EM Probe

Crone Geophysics has developed a pulse EM slim hole tool operating in the 6 to 8 KHz range. While the tool has been developed to map sulphide zones it can be used for identifying conductive clays or pore water with high conductivities. At least one oil sand operator has considered testing the tool for identifying conductive clays. If conductive clays relate to low strength or some other geotechnical property, the tool may be worth testing.

7.4.15 Other Applications

Groundwater Exploration and Research Ltd. (R. Nowak) is using standard tools by OYO, Keck and SIE for developing methods to obtain cation exchange ratios in clay and Atterburg Limits from the standard logging suites. They are also involved in developing a method to measure resistivity in plastic cased holes in unconsolidated sediments.

7.5 Summary

The foregoing methods, probes and systems represent a selection of relevant tools which are either in the prototype stage, have been only recently developed on a commercial basis, or are relatively unknown in coal and oil sands. It is suggested that all of these systems should be given a more critical examination in the second phase of this study. Several cross-borehole techniques, the RIM, fluid flow devices and the scanning devices seem to be potentially useful.

8. SOFTWARE FOR GEOPHYSICAL LOGGING

All modern geophysical logging equipment has digital capability and the field data are stored on either floppy discs or multi-track tape. Therefore it is essential that proper software be available for satisfactory plotting and interpretation of the field data. General inquiries have indicated that though several geophysical logging software packages are available, there is no single specific package that will likely meet all the demands that will be generated by this project (see list below). Therefore it will be necessary to have a mix of publicly-available programs of a general nature, and programs or subroutines developed specifically for this project. The compatibility of the software for the selected equipment (hardware) should be another consideration.

Some of the specific purposes for which software is required are the following: plotting of logs and general data presentation; statistical analysis of data; and special mathematical operations. Additionally, in most systems computer-assisted processing of raw data is necessary in order to obtain the logs.

Statistical processing of data is particularly useful in the case of logs in which there is an inherent scatter in the data, and this includes all nuclear logs and some electrical logs. The simplest statistical treatment consists of the production of histograms, and parameters such as mean, standard deviations and range. Numerous packages for such treatment are available. Cross-plots are also widely used for a visual representation of the degree of correlation between two parameters, calculating the matrix corrected porosity and the structural and geological implications of such correlations. Cross-plot routines are widely available, or can be written in a short time by someone with some programming experience.

To obtain the dynamic moduli of overburden and bedrock material, it will be necessary to perform simple mathematical operations on data involving seismic velocities and density. This is a simple programming task, though automatic picking of events in order to calculate the velocities, is a more formidable task.

Many logging techniques require complex processing of the raw data, e.g. tomographic processing. However such processing would be specific to a system, and would be provided by its supplier.

Since no single specific software package will be completely suitable for this project, the following course of action is recommended. First, the specific operations that are required, e.g. histogram generation, cross-plots, etc., should be identified. Then, it should be determined which software packages available are most suitable for the project objectives. Arrangements should be made to develop the necessary additional or project specific software required.

Following is a partial list of available general log analysis software:

E S Log, Energy Systems Technology, Englewood, Colorado
Log Mate, D and S Petroleum, Calgary, Alberta
Terralog, Terra Sciences, San Ramone, California
PAS System, Petroleum Computing, Dallas, Texas
Log Calc II, Scientific Software, Calgary, Alberta
software, Mt. Sopris, Delta, Colorado
software, Dr. Dusseault, University of Waterloo, Waterloo, Ontario
software, BPB Instruments, Calgary, Alberta
software, GEONA Enterprises, Calgary, Alberta
Logger, Rockware Inc., Denver, Colorado
ELOG, Sinclairville Petroleum Corp., Westfalls, N.Y.
LOGIT, Software Associates, Westerville, Ohio
Log Analysis, Buckner Project, Houston, Texas
EZ-Log, Geosphere Software, Houston, Texas

Most of these systems were designed for the oil industry. Some have been designed with the mineral industry needs in mind. Several suppliers have also indicated a willingness to make modifications or additions that may be required.

Most of the programs listed are able to perform the types of analyses outlined. From experience, one of these programs, Terralog, can utilize the digital data from almost any tool or source with very little additional effort. Nine track tape is the most flexible medium for data transfer and storage, although floppies

are also used. Experience has shown in other related work that data is needed on a very small increment such as 1 cm. On this basis a drill hole of any substantial depth will generate a very large file.

Geona Enterprises has developed, with the support of the Federal Government, a relatively sophisticated software package for reducing standard geophysical suite data in oil sands to derive a number of geotechnical/hydrogeological parameters including type of pore water, cement volumes, grain size data etc. It would appear that this package could be modified to handle coal and associated overburden logs. Testing of this software is merited.

At a minimum the system chosen for use will require the following abilities:

1) Data entry and Storage capabilities

- a) multiplex data
- b) string data
- c) raw digitized data

2) General Conveniences, such as:

- a) help commands
- b) depth setting
- c) selection of depth frequency
- d) depth scaling
- e) metric compatibility
- f) screen or page annotation
- g) easy log selection

3) Data Handling

- a) data base
- b) files
- c) functions, such as:
 - 1) modify one or more logs
 - 2) compute channel sum
 - 3) eliminate data outside limits
 - 4) adjust logs based on compared values
 - 5) perform selected operations

4) Data Display

- a) echo
- b) scan
- c) status report
- d) histogram
- e) log plotting
 - 1) define configuration
 - 2) modifications
 - 3) adding and removing curves from display
 - 4) shading
 - 5) reference depth
 - 6) reference lines
 - 7) lithologic column

5) Other

- a) crossplots
 - 1) frequency
 - 2) regression
 - 3) zplot
 - 4) three component plots
 - 5) lithodensity plot
- b) various output options

6) A sophisticated petrology computation ability

7) The integration of different elements like:

- a) those used in classical reservoir analysis,
- b) synthetic seismograms,
- c) the ability to compute indexes such as rock strength,
- d) the ability to merge multiple plots as overlays.
- e) sufficient work space to handle at least 50 channels or plots of information

8) The ability to handle and assist in the analysis of dip meter logs

9) General statistical abilities

10) Clear presentation of outputs in a user defined format.

Use one or more of the currently available packages provides a starting point for continuation of this project. It will probably be necessary to write some additional software for specific requirements.

9. SUMMARY AND CONCLUSIONS

9.1 General

The review of the current "state-of-the-art" use of borehole geophysics shows that there are techniques available with the potential to provide some of the geotechnical and hydrogeological parameters desired. Most of these techniques were originally developed for either the petroleum or hard rock applications.

The reliability and effectiveness of these techniques in the shallow, soft rock typical of the western Canadian coal and oil sands mining situations has not been fully evaluated or in some cases even attempted.

Many of the desired parameters can apparently be derived from the geophysical logs currently being obtained by the mining and exploration companies as part of their ongoing programs. These geophysical logs are obtained for identifying lithological and interpreting geological structures. Typical logging suites in the coal and oil sands operations include:

- Caliper
- Natural Gamma
- Gamma-Gamma (Density)
- Resistivity (short, long or focussed)

Additional logging has been done including:

- Neutron-Neutron
- Dipmeter (3 or 4 Point Resistivity)
- Sonic

These logs when combined with correlation data from laboratory tests and field tests (uniaxial compressive strength and falling head tests for example) will allow an initial evaluation of many of the techniques without additional field data collection.

9.2 Parameters and Probes

A wide variety of geophysical borehole probes are available, all of which measure a physical characteristic of the material under investigation. This physical characteristic is rarely a direct measurement of the actual parameter of interest but be correlated to the parameter in some manner. For example, a dipmeter does not record the strike and dip of the geologic unit; it measures the resistivity of a small part of the borehole. By combining the three or four resistivities recorded at the same time, a mathematical manipulation can interpret the strike and dip of the various layers in the structure. Many of the geological and hydrogeological parameters will only be derived by combinations of various probes and techniques.

The summary of the literature and current research suggests that the following probes can be used to predict the associated parameters.

The Caliper probe is used mainly to correct the data from other tools for the variations in hole diameter. It can also indicate the structural competence of the various rock types.

The natural Gamma tool provides clay content data which is important in determining lithology, structural features and possibly permeability. Spectral gamma logs provide information on clay mineralogy.

The Gamma-Gamma (density) tool is the primary tool for determining material density. It can also be useful in interpreting porosity.

Neutron-neutron tools are used extensively in the oil and gas industry for determining porosity and moisture content.

Resistivity logging is currently used for lithological analysis and contact definition but is reported to have potential for determining moisture content and saturation and has been used for water quality.

The dipmeter is a variation on the standard resistivity tool that provides strike and dip measurements of the geologic structure. There may be some possibility of determining joint sets.

Induction logs are most likely to be useful in determining water quality and saturation of surficial materials.

Both the acoustic televiewer and borehole television systems can provide a detailed picture of the borehole wall allowing the geologist to examine bedding, contacts, material types and to make strike and dip measurements.

Radar has the potential, in areas of varying conductance, to map the structures and fractures. Of particular note is its ability to penetrate long distances in suitable materials. Initial indications suggest, however, that the plains overburden materials are poorly suited to this approach.

Radio imaging, both downhole and crosshole, has uses in fracture and fault mapping and lithological determination and correlation.

The various flowmeters can provide information on in-situ water flow, and aquifer identification. Temperature probes and flowmeters provide information on relative yield.

Table 3 provides a quick summary of the various probes and the parameters to which they can contribute information. It is apparent from the literature reviewed that there is no reported technique for determining pore pressure.

9.3 Data Manipulation Software

As most of the techniques are based on the numerical manipulation and combination of the various geophysical logs, a computer software package capable of inputting, sorting and displaying these logs is the only efficient method for fully evaluating these techniques. A key component of a software system for evaluations of this type will be the ability to allow user input of new evaluation approaches or modifications to the currently available models.

TABLE 3
CHART OF APPLICATIONS

Geophysical Tool Parameter	Caliper	Natural Gamma	Gamma Gamma density	Neutron Neutron	Resist.	3 point Resist. dipmeter	Sonic Tube Wave (VSP)	Gravity meter	Flow- meter	Temp.	Radar	Holog.	Acousti & Borehol Televis.
Lithology	*	*	*	*	*		*						*
Geological Structure		*			*	*	*				*		*
Density	*		*	*			*	*					*
Rock Quality Designation	*			*	*	*	*						
Compressive Strength				*			*						
Shear Strength							*						
Elastic Properties							*						
Stress Distribution												*	
Fractures	*		*			*	*				*		*
Grain Size Dist.		*	*			*							*
Pore Pressure													
Moisture Content			*	*	*				*				
Water Flow								*	*	*			
Porosity			*	*	*		*						
Permeability		*						*	*	*			
Water Quality								*					

Note: Any particular parameter may require more than one of the identified tools.

There are several software packages available to handle almost any type of geophysical log. Many of the packages already have manipulations built in to determine some of the desired parameters. These modelling techniques were generally developed for other applications such as oil and gas and may be fully applicable to the coal and oil sands environment with only limited modification.

Selection of specific packages to use for the evaluations will depend on the availability of hardware and suitable logs for the specific evaluations.

10. RECOMMENDATIONS

The following recommendations for further work are made:

1. Select one or two computer software packages and evaluate their ability to reliably produce the desired parameters in the coal and oil sands environments from currently available log and laboratory data. This recommendation is the main component of Phase 2 of the project as originally conceived.
2. Evaluate the cost effectiveness of using these techniques to obtain the hydrogeological and geotechnical parameters.
3. Review and recommend which additional geophysical logging systems have the potential to produce additional parameters in a cost effective manner for which no western Canadian data are available.
4. Continuing contact with other workers in this field should be considered to enable the project to stay current with ongoing developments. Areas of particular interest are pulsed neutron tools, crosshole seismic tomography and acoustic televiewers.
5. Research into geophysical techniques for determining pore pressure should be conducted.

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APPENDIX I

PROJECT ORGANIZATION AND MANAGEMENT

APPENDIX I

1. Management Committee

The project is governed by a Management Committee that provides overall direction to the Hydrogeological and Geotechnical Committees conducting the study. This includes responsibility for project content and budget control, as well as responsibility for selection of the final technical and expert committee members.

The following individuals have been appointed to the Management Committee:

- D. Nikols, TransAlta Utilities Corporation (Chairman)
- D. Scott, Civil Engineering Department, University of Alberta
- E. Fraser, Suncor Inc.
- N. Wade, Monenco Consultants Limited
- G. Jenkins, Chairman, Geotechnical Committee, Manalta Coal Limited
- A. Hickinbotham, Chairman, Hydrogeological Committee,
TransAlta Utilities Corporation
- T. Sneddon, Alberta Office of Coal Research & Technology
- B. Das, CANMET: Energy, Mines & Resources, Canada

2. Geotechnical Committee

This committee is responsible for the scope of the geotechnical component of the study, technical procedures, and for making recommendations to the Management Committee with regard to selection of competent geophysical and geological professionals to conduct the research.

The following representatives comprise the Geotechnical Committee:

G. Jenkins, Manalta Coal Ltd., (Chairman)
B. Das, CANMET: Energy, Mines & Resources, Canada
I. Rozier/P. Stacey, Golder Associates
A. Leach, Kohn Leonoff Ltd.
F. Khan, Terracon Geotechnique Ltd.
N. Wade, Monenco Consultants Limited

3. Hydrogeological Committee

Similarly, the Hydrogeological Committee is responsible for the scope and procedures within the hydrogeological component of the study.

The committee is comprised of the following representatives:

A. Hickinbotham, TransAlta Utilities Corporation, (Chairman)
M. Trudell, Alberta Research Council
L. Pitts, Monenco Consultants Limited
N. Worsley, Saskatchewan Power Corporation
T. Dabrowski, Piteau Associates Engineering Ltd.
L. Nichols, Terracon Geotechnique Ltd.
G. Lobb, Syncrude Canada Ltd.

4. Project Manager

The administration of the project and coordination of subcontractors is carried out by the Coal Mining Research Company acting as project manager, under the direction of the Management Committee. Additional responsibilities include technical and financial progress reports to the Management Committee, as well as preparation of project reports.

5.

Expert Review Panel

The expert review panel has been selected to review the results of the research conducted during the project and to advise on the content and procedures required in subsequent phases. Panel members include:

S. Keys	United States Geological Survey, Denver, Colorado (Retired)
P. Killeen	Geological Survey of Canada
J. Mwenifumbo	Geological Survey of Canada
C. Brawner	University of British Columbia
N. Morgenstern	University of Alberta
R. Bishop	BPB Instruments, (Canada) Ltd.

APPENDIX 2
KEY WORD LIST

CONCEPT DELINEATION OF KEYWORD LIST FOR
DOWNHOLE GEOPHYSICS RESEARCH PROJECT

(1) GEOPHYSICAL GENERAL

geophysics
borehole geophysics
downhole geophysics
geophysical logs
logs
borehole logs

(2) LOGGING METHODS

well logging (tools)
wireline logging (tools)
nuclear logging
logging tool
seismic
shear wave
borehole televiewer
induction logging
borehole camera

(3) LOG TYPES

sonic log/logging
acoustic log
density log
caliper log
resistivity log
gamma log
electric log
apparent density log
bulk density
gamma-gamma
radioactive log
natural gamma log
fluid log
neutron activation log

(4) GEOPHYSICAL TERMS

dipmeter (diplog)
cycle skipping
crosshole
velocity
wavelet
neutron
geophone
strength index
elastic moduli
dynamic moduli
petro physics
flowmeter
gamma spectrometry
log interpretation
log analysis
synergistic analysis

flowmeter
gamma spectrometry
log interpretation
log analysis
synergistic analysis

(5) HYDROGEOLOGICAL GENERAL

ground water
groundwater
water quality
water chemistry
groundwater chemistry
hydraulic
hydrogeology
hydrogeologic

(6) HYDROGEOLOGIC PARAMETERS

pore pressure/hydraulic head
hydraulic conductivity
porosity
effective porosity
storativity
specific yield
yield
secondary porosity
permeability
fracture

(7) HYDROGEOLOGICAL TERMS

transmissivity
aquifer
aquitard
water table
groundwater flow
groundwater conductivity

(8) GEOLOGICAL

geologic
shear plane
glacial thrusting
joint orientation
deformation
structure
consolidation
lithology
fracture zones
bedding
subsurface
core
faults
folds
texture
cementation
hardness
permeability
stratigraphy
cementation

hardness
permeability
stratigraphy
cementation

(9) SOIL MECHANICS

geotechnical
soil strength
in situ
preconsolidation
compaction
effective stress
liquid limit
Atterberg limits
failure criteria
Mohr's circle
shear strength
compressive strength
cohesion

(10) ROCK MECHANICS

geomechanical
rock strength
rock mechanics
rock fabric
competency
strength properties
stress
durability
elasticity
dynamic properties

(11) MINING TERMS

mine engineering
slope stability
blasting
diggability
trafficability
slope failure
highwall failure
landslide
footwall
seatearth
strip mining
open cast
mine planning
coal mining

(12) OILSANDS TERMS

tar sands
oil sands

APPENDIX 3

BOREHOLE GEOPHYSICAL EQUIPMENT

DOWNHOLE GEOPHYSICAL LOGS(GENERIC):

Electrical Methods:

Single point resistance
Resistivity (40,80 & 160 cm separations)
Spontaneous potential
Fluid resistivity
Focused beam resistivity
VLF-EM (very low frequency electromagnetic)
Radar; single hole and crosshole
Electromagnetic; single hole or crosshole
Electromagnetic; surface to downhole
Dipmeter
Induced Polarization

Radiometric Methods:

Natural gamma; broadband or spectrometry
Density (gamma-gamma)
Porosity (neutron-neutron)

Seismic Methods:

Sonic; velocity, amplitude and full waveform
Tube waves; surface to downhole
Crosshole seismic (can include tomography)

Thermal Methods:

Temperature Measurements
Heat-pulse flowmeter

Others:

Aquifer Tide

Impulse Flowmeter

Television:

Acoustic Televiwer:

Magnetic Susceptibility

Caliper

GEOPHYSICAL LOGGING EQUIPMENT (BY MANUFACTURER):

APPLIED ELECTRONICS LTD.,
299 Evans Ave., Toronto.M8Z 1K2.
Tel: 416 252-3761.

Agent for Rees television system of UK.

BISON INSTRUMENTS INC.,
5708 West 36th Street,
Minneapolis. Minn. 55416 USA
Tel: 612 926-1846.

Crosshole Shear Wave System:

The system consists of shear wave hammer, geophones and engineering seismograph. Dynamic moduli of the rock volume can be computed. 60 m operable length; up to 30 m hole separation.

Also Magnetic susceptibility equipment.

COMPROBE, INC.,
9632 Crowley Rd. Crowley,Tx, 76036.USA.
Tel 817 293-7333.

Natural gamma, neutron, temperature, differential temperature, fluid resistivity, caliper, density; up to 4500 m cable length; 1, 4 or 7 conductor; digital capabilities on 9-track tape, an LSI-11 based system; variable tool diameter, but most less than 75 mm.

EASTMAN
P.O. Box 1160,
Carl-Zeiss-Strasse 16,
3005 Hannover - Westerseld,
West Germany.

Borehole television system

Geologger-3000:

Resistivity, microresistivity, spontaneous potential, temperature, caliper, density, natural gamma, magnetic susceptibility; 4 conductors; 310 m length; not known whether digital recording is possible; all tools of diameter less than 50 mm.

Geologger-3400:

Natural gamma, single-point resistance, spontaneous potential, density, resistivity, temperature and differential temperature, caliper, fluid resistivity and sonic velocity; limited digital storage capability, details unknown; all tools except sonic of 32 mm diameter, sonic of 46 mm diameter.

EG&G GEOMETRICS MOUNT SOPRIS DIV.
P.O. Box 449, Delta, Colo. 81416.
Tel: (303) 874-5711.

Model 1000-C:

Backpack portable; single-point resistance, spontaneous potential and natural gamma are the basic logs available on this system. Some other probes e.g, density, porosity and spectral gamma can also be attached after modifications. No digital capabilities. 300 m cable; single conductor. Probe diameter 50 mm or less

Model II:

Lightweight system of weight about 100 kg. Sonic, flowmeter, fluid resistivity, gamma, density, porosity, resistance, resistivity, focussed-beam resistivity, temperature and caliper are available. Cable up to 760 m. Digital recording on cassette and possibly floppies. Most tools of diameter 60 mm or less.

Model III:

Sonic amplitude, transit time and full waveform; borehole deviation (magnetic), caliper, dipmeter, fluid resistivity, induced polarization (time domain), induction, natural gamma, resistance, 40-and 80-cm resistivity, single and dual spaced gamma-gamma, spontaneous potential, spectral gamma, temperature, thermal neutron and other specialized tools. Fully digital, on cassettes, floppies or nine track; can be mated to a micro or a mini. Most tools of diameter less than 50 mm; some up to 60 mm. 4-conductor cable up to 3 000 m. Has to be truck mounted.

IBAK

Wehdenweg 122; Postsach 6260,
D-2300 Kiel 14. West Germany.

Downhole television system; colour capability.

MCPHAR RADIOMETRICS,
Tel: 416 477-5766.

Multilog-3:

Natural gamma, single-point resistance, self-potential.; single conductor; 350 m length; no digital capabilities; 32 mm tool diameter; backpack portable. (Currently not in production).

RD-600:

Spectral gamma, self potential, single-point resistance and resistivity. Digital recording, mated to LSI 11 computer.
It has been reported that McPhar is also developing a temperature logger.

MINERAL LOGGING SYSTEMS, INC.

8821C Forum Way, P.O. Box 40498,
Fort Worth, TX 76140, USA.
Tel: 817 293-1777.

Natural gamma, neutron, density, temperature, flowmeter, sonic, caliper, fluid resistivity, focussed beam, resistance; digital recording, on cassette mated to a Hewlett Packard 85 computer; length up to 4 000 m; most tools less than 50 mm diameter. Various " series" are possible by combination and permutation of components.

OYO CORPORATION, INSTRUMENTS DIV.,

2-19 Daitakubo 2-Chome, Urawa,
Saitama 336 Japan. Tel 0488-82-5371

In Canada:

Romor Equipment Ltd., 1083 Britannia Road E.
Mississauga.Ont.L4W 3X1. Tel 416-671-3209

Geologger-300:

Very light (6 kg) backpack portable; resistivity, spontaneous potential. Temperature and caliper also possible. Single conductor. No digital capability. 310 m cable length. Tools of less than 50 mm diameter.

ROBERTSON RESEARCH ENGINEERING SERVICES LTD; GEOLOGGING DIV.,

TYN-Y-COED, LLANRHOS,
LLANDUDNO; GWYNEDD LL301SA,UK.
Tel: (0492) 81811.

Geolog 1000:

Natural gamma, dual density, fluid resistivity, temperature, density, 40-, 80- and 160-cm resistivity, focussed-beam resistivity, flowmeter (impeller and heat-pulse), caliper, and other specialized tools. Most tools less than 50 mm diameter. Length 1000 m. Four conductor cable. Fully digital. Recording on cassettes and possibly other media.

SCINTREX LTD.,

222 Snidercroft Road, Concord.Ont.L4K 1B5.
Tel: 416 669-2280

Borehole logging systems are not the principal products of Scintrex. However, a perusal of their catalogue shows that they offer the following products: spectral gamma; electromagnetic borehole logging; induced polarization/resistivity and a specialized tool the "metalog", which could be modified to yield ash content in coal.

SHIMUZU CONSTRUCTION CO.

Tokyo, Japan.
Borehole television system; colour capabilities.

SIMPLEC MANUFACTURING CO INC.,
4230 Shilling Way,
Dallas, Texas. 75237. USA.
Tel 214 330-0406.

Acoustic televiewer system. Cable length up to 2 000 m.

SOLINST CANADA LTD.,
5 - 2440 Industrial Street,
Burlington. Ont. L7P 1A5.
Tel: 416 335-5611

Downhole television system.
II tools of diameter less than 50 mm.

Geologger-3400:
Natural gamma, single-point resistance, spontaneous potential, density, resistivity,
temperature and

GEOPH.LOGGING RESEARCHERS (BY INSTITUTION):

ATOMIC ENERGY OF CANADA LIMITED.,

Applied Geoscience Branch, Whiteshell Nuclear Research Establishment, Pinawa.
Man. R0E 1L0.

Principal Contact: Dr. Nash Soonawala.
Tel 204 753-2311.

Dzintars K. Tomsons, N. Soonawala, general logging; Mt.Sopris Model I and Model III.

Peter Hurley; crosshole seismics, tomography; fully operational equipment developed by AECL/U of Toronto.

Cheng F. Huang; tube waves; fully operational equipment developed by AECL/GSC.

John G. Hayles; VLF-EM.

Joe Lau; borehole television and acoustic televiewer. Sperry and Simplec equipment.

Cliff C. Davison; hydrogeological applications.

GEOLOGICAL SURVEY OF CANADA

Dr. Patrick G. Killeen, Exploration Geophysics Subdivision, Mineral Resources Div., Geological Survey of Canada, 601 Booth Street, Ottawa. Ont. K1A 0E8. Tel:613 996-2312.

Expert in general logging; primary interest, nuclear logging; mostly nuclear equipment of own design or heavily modified.

Dr. Jonathan Mwenifumbo, same address as above.

Electrical methods; experimental equipment, mostly mise a la masse.

Dr. Malcolm Drury, Geothermics, Geophysics Div., Geological Survey of Canada, 1 Observatory Cresc. Ottawa. K1A 0Y3.

Tel 613 995-5478.

Thermal logging; portable thermal logger.

Leonard S. Collett, 601 Booth Street, Ottawa K1A 0E8

Tel: 613 993-5964

General logging, radar.

Don Bower, Geophysics Div.,

Geological Survey of Canada,

1 Observatory Cresc. Ottawa. K1A 0Y3

GEOSEISMO OY

Valimotie 23C, SF-00380 Helsinki, Finland
Calim G. Cosma, crosshole seismics.

INSTITUTE OF GEOLOGICAL SCIENCES,
Building 151,
Harwell Laboratory, Oxon. OX11 0RA. UK
Dr. David M. McCann; crosshole seismics.

ISMES,
Via T. Taramelli 14,
I-00197 Rome, Italy
Dr. F. Gera; crosshole seismics.

JODEX APPLIED GEOSCIENCE,
40 McGillvray Av.
Toronto. M5M 2Y1. Tel: 416 483-7724.
Dr. Joe Wong, full waveform sonic, crosshole seismic, tomography. Will provide logging services, and might manufacture and sell downhole equipment.

LAWRENCE LIVERMORE NATIONAL LABORATORY
P.O. Box 808,
Livermore. Calif. 94550. USA.
Dr. Abe Ramirez; Tel 415 422-6909; electromagnetic tomography.

MCGILL UNIVERSITY
Dept. of Geological Sciences,
Montreal. H3C 3G1.
Tel: 514 392-5950
Contact: Dr. W. Murray Telford;
Dr. Jean Roy, presently overseas, general logging; VLF-EM.

QUEEN'S UNIVERSITY,
Dept. of Geological Sciences,
Kingston. Ont. K7L 3N6.

Dr. Paul Young; crosshole seismics tomography. Tel: 613 547-2798.

Dr. Alfred V. Dyck, electrical methods.

SOUTHWEST RESEARCH INSTITUTE,
6220 Culebra Road,
San Antonio. Texas. 78023.
Contact: Tom Owen (512) 684-5111
Radar, and numerous other geotechnical methods.

SWEDISH GEOLOGICAL CO.

Box 1424, 75144 Uppsala, Sweden.

Dr. Olle Olsson; radar logging, also possible contact for crosshole seismic. Tel: 018-156420

UNITED STATES GEOLOGICAL SURVEY.

Dr. Frederick L. Paillet, Borehole Geophysics Research Project, USGS, MS 403, Denver Federal Center, Denver. Colo. 802205.

Tel: 303 236-5913.

General logging, full waveform sonic, heat-pulse flowmeter; very sophisticated equipment.

Dr. David Wright, USGS, MS964,

Denver Federal Center, Denver. Colo. 80225.

Tel: 303 234-5462.

Radar logging; self-designed and developed equipment.

UNIVERSITY OF TORONTO

Dept. of Physics,

Toronto. M57 1A7

Dr. Gordon F. West, crosshole seismics, electromagnetic induction methods; Tel 416 978-3155.

Ken Howard, general logging.

UNIVERSITY OF WATERLOO

Dr. John Greenhouse, logging in overburden.

APPENDIX 4

EQUIPMENT SUPPLIERS, CONTRACTORS AND RESEARCHERS

A: Equipment Supplier & Contractors

B: Researchers

A: EQUIPMENT SUPPLIERS AND CONTRACTORS

COMPANY

CONTACT & TELEPHONE

A-Cubed
5566 Tomkem Road
Mississauga, Ontario
L4W 1P1

Dr. A.P. Annan
(416)624-8878

Alpha Nuclear
6380B Viscount Road
Mississauga, Ontario
L4V 1H3

Jeff Denham
(416)676-1364

Atomic Energy Canada Ltd.
Pinawa, Manitoba

Dr. N. Soonawala
(204)753-2311

BPB Instruments Ltd.
5915C - 36th Street S.E.
Calgary, Alberta

Richard Bishop
(403)234-9144

Century Geophysical Corporation
of Canada
5911 - 5th Street S.E.
Calgary, Alberta

Andrew Cicoria
(403)255-1110

CGG
Suite 300, 2500 Wilcrest
Houston, Texas
77042

(713)784-0740

Comprobe Instruments
6932 Crowley Road
Crowley, Texas
76036

Glen Breau
(817)293-7333

Computalog Gearhart Ltd.
1917 - 84 Avenue
Edmonton, Alberta

Philip Hnatiuk
(403)464-6107

Crone Geophysics Ltd.
3607 Wolfedale Road
Mississauga, Ontario
L5C 1V8

Duncan Crone
(416)270-0096

Delft Soil Mechanics Laboratory
Stieltjesweg 2
P.O. Box 69
2500 AB Delft
The Netherlands

M. Kroezen
015-569223
Telex: 38234 Solabnl

A: EQUIPMENT SUPPLIERS AND CONTRACTORS (cont'd)

COMPANY	CONTACT & TELEPHONE
Dresser-Atlas 1200, 505 - 3rd Street Calgary, Alberta	Jerry Manly (403)290-5100
EG & G Geometric Mt. Sopris Instruments Division P.O. Box 449 Delta, Colorado 81416	John Stowell (303)874-5711
Exploranium 55 Healey Road, Unit 5 Bolton, Ontario L7E 5A2	John Cox (416)857-3670
Gearhart Industries P.O. Box 1936 Fort Worth, Texas 76101	
Geonic Limited 1745 Meyerside Road Unit #8 Mississauga, Ontario	J.D. McNeill (416)676-9580
Geotech 20-101 Amber Street Markham, Ontario L3R 3B2	Scott Holladay (416)473-6999
Huntec (70) Limited #303, 3130 Lawrence Aven. East Scarborough, Ontario M1R 5C7	Jack Dodds
I.F.G. 18 Bram Court Unit 5 Brampton, Ontario L6W 3R6	Detlef Blohm (416)451-5228
Keck 1099 West Grand River Williamston, Michigan 48895	Dan Tuttle (517)655-4391
Lamontagne Geophysics Ltd 49 Spadina Ave. Toronto, Ontario M5V 2J1	Y. Lamontagne (817)293-7333

A: EQUIPMENT SUPPLIERS AND CONTRACTORS (cont'd)

COMPANY

CONTACT & TELEPHONE

McPhar Geophysics
3400 - Fourteenth Street
Markham, Ontario

Bradley Stevens
(416)477-5766

Mineral Logging Systems
Subsidiary of Gearhart Industries
8821C Forum Way
P.O. Box 40498
Fort Worth, Texas
76140

Charles Dickson
(817)293-1300

Neltronic Instrument Corp.
4319 Stanford
Houston, Texas
77006

Frank Geraghty
(713)523-2546

OYO Corporation
Instruments Division
2-19 Daitakubo 2 - Chome, Urawa
Saitama 336 Japan

0488-83-5371

OYO Corporation
(Canadian Representative)
Romor Equipment Ltd.
1083 Britannia Road E.
Mississauga, Ontario
L4W 3X1

Robert Morgan
(416)671-3209

Phoenix Geophysics Ltd.
200 Yorkdale Blvd.
Willowdale, Ontario
M2J 1R5

P.G. Hallof
(416)477-8588

Robertson Research Eng. Services
Llandudno
Gwynedd LL301SA, U.K.

R.G. Williams
(0492)81811

Roke Oil Enterprises Ltd.
516 Moraine Road N.E.
Calgary, Alberta

Keith Banks
(403)273-5553

Schlumberger
801 - 6th Ave.
Calgary, Alberta

Mike Standford

Scintrex
222 Snidercroft Road
Concord, Ontario

Dr. S. Nargolwolla
(416)669-2280

A: EQUIPMENT SUPPLIERS AND CONTRACTORS (cont'd)

COMPANY	CONTACT & TELEPHONE
S.G.A.B. Swedish Geological Box 1424, S-751 44 Uppsala, Sweden	Mr. O. Olsson
SIE Division of Geosource Inc. 105 - 61671 Ave. S.E. Calgary, Alberta	Don Farney (Calgary) (403)253-2135
Simplec Manufacturing Co., Inc. 4230 Schilling Way Dallas Texas 75237	George Cimpoz (214)330-0406
Stolar 2715 - J Broadbend Parkway Albuquerque, New Mexic 87107	Bill Mondt (505)345-7871
Urtec Instrument Sales Ltd. 131 Telson Road, Unit 6 Markham, Ontario M4T 1N6	Frank Bottos (416)475-1133

B: RESEARCHERS

CONTACT

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Project Head Geophysics
P. Bag X256
Pretoria, South Africa

Mr. Andrew Black
Geophysicist
605 Parfet Street
Denver, Colorado

Dr. Mihai Borsaru
Senior Research Scientist
339 Williamstown Road
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Determining Geotechnical and Hydrogeological
Parameters Using Downhole Geophysics
in the Canadian Plains

Phase 2 Report

CORRELATIONS OF EXISTING DATA

May 1988

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on behalf of the

DOWNHOLE GEOPHYSICS
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MICROMEDIA

246 pp

EXECUTIVE SUMMARY

The Downhole Geophysical Project resulted from the desire of several resource companies and geoscience consulting firms to improve the cost-to-data ratio of obtaining hydrogeological and geotechnical information for both coal and oil sands mining operations.

Proposals for joint industry and government research funding were prepared and submitted. The acceptance of these proposals for 50/50 industry/government funding by the Alberta and Canadian Governments resulted in the commencement of the project in November 1986. The project was divided into three phases, the results of the second phase being reported here.

The objective of the second phase is to evaluate through correlation whether various geotechnical and hydrogeological parameters could be obtained from downhole geophysics and to review which tools, not currently in use in Alberta, might have potential to provide the desired parameters.

This project used existing data that were collected with normal industry practices to develop site specific empirical correlations. The project has demonstrated that trends are present and correlations can be made but the variance of data scatter makes the direct use of the correlations questionable without further study.

Based on this program, one of the participants is investigating the use of the sonic log to determine the diggability of material in the selection of mining equipment.

At one coal mining operation, the geophysical logs that give the best correlations with geotechnical data are the Neutron, Density and Sonic Logs. The data also shows that good correlation was obtained between unconfined compressive strength and sonic transit time. For those relationships which exhibit correlation coefficients less than 0.8, the correlation may be improved by increasing the number of observations, by pairing combinations of parameters, by considering individual lithologic units or by more rigorous scrutiny of data to ensure consistency.

For one oil sands mining operation, the geophysical logs that provided trends were the Density and Gamma Logs when paired with different geotechnical parameters. All of the correlations have a wide scatter of data and could probably be improved by closer examination of the data.

Based on this study, it appears that the hydraulic conductivity cannot be estimated from geophysical parameters. Weak trends are indicated with the Density, Focussed Electric, and Neutron Logs. Additional analysis is required with existing data to further develop the data set used in the correlations.

A specifically designed program is recommended to obtain detailed geotechnical, geophysical, and hydrogeologic data from a series of carefully cored and logged holes. This should be done on a site specific basis in different types of coal or oil sands formations.

The programs should be run using the standard logging tools which include the gamma probe, the sonic tool, Neutron, and the gamma-gamma or density tool. If sufficient funds are available, a group of new tools such as the Radio Imaging Method and Thermal Logging Tools should be considered for future use.

Major problems were encountered in selecting and sorting of data. Existing data bases of geotechnical, geophysical and hydrogeologic data could not be easily related. These problems are discussed further in the text of the report.

Stricter recording of field data is required in field drilling and logging programs. This should include:

- . tool calibration and field standardization
- . borehole fluid conductivity and density
- . exact location of geotechnical tests
- . proper location of piezometer screens, sand pack in the aquifer zone

PREFACE

This report reviews the work done and results obtained in the use of existing downhole geophysical, geotechnical and hydrogeological data to determine the relationships between the borehole geophysics and the desired physical parameters. The results reported in the following chapters are based on the work completed as Phase 2 of the Downhole Geophysics Project undertaken as a joint industry/government research investigation. The project joint venture is funded by the following companies and organizations:

Alberta Office of Coal Research and Technology (AOCRT)

Alberta Research Council (ARC)

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Manalta Coal Ltd.

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TransAlta Utilities Corporation

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Robert Wilson	Coal Mining Research Company (CMRC)

The Downhole Geophysics joint venture project is directed by a management committee chaired by Mr. Andrew Hickinbotham of TransAlta Utilities. TransAlta is acting on behalf of the industry joint venture participants for purposes of entering into Research Funding Contracts with Supply and Services, Canada and the Alberta Office of Coal Research and Technology.

The work plan organization, control and reporting was supervised by a Geotechnical Committee chaired by Mr. Geoff Jenkins of Manalta Coal and a Hydrogeological Committee chaired by Mr. Lloyd Pitts of Monenco Consultants Ltd.

In addition a panel of experts consisting of the following individuals reviewed the work in progress, commented on various drafts of this report and made many useful suggestions.

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This report and its contents, the research project in respect of which it is submitted and the technology produced or demonstrated in the research project do not necessarily reflect the views of the Government of Alberta, its officers, employees or agents (or of the Alberta/Canada Energy Resources Research Fund Committee) or of the Members of the Office.

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The research project for which this report is submitted was administered by the Alberta Office of Coal Research and Technology and was funded (in part) from the Alberta/Canada Energy Resources Research Fund, a fund jointly established by the Government of Canada and Government of Alberta.

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DOWNHOLE GEOPHYSICS PROJECT

PHASE 2 - 1987/88

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1. INTRODUCTION

1.1 Project Formation

The Downhole Geophysics project was formed in the spring of 1986 by a group of resource and consulting companies which desired to find methods of reducing the cost of obtaining hydrogeological and geotechnical information for coal and oil sands mining operations.

Phase 2 of this project was conducted during the 1987/88 fiscal year under the direction of several working committees and a management committee chaired by Mr. Andrew Hickinbotham of TransAlta Utilities. The details of the management and technical committees are described in Appendix 1.

Funding for this phase of the project was provided by the industry participants on a 50/50 basis with the supporting government agencies. The coal portion was supported by the Alberta Office of Coal Research and Technology and the oil sands portion by Supply and Services Canada in cooperation with CANMET.

1.2 Background

The Phase 1 report (TransAlta Utilities Corp., 1987) described the potential for reducing costs to the western Canadian resource and consulting companies by the use of downhole geophysics to determine geotechnical and hydrogeological parameters. The initial review of the "state-of-the-art" reported in Phase 1 indicated that there were potential correlations between the downhole geophysics and some of the geotechnical and hydrogeological parameters of interest.

The recommendations to evaluate these suggested correlations on existing data formed the basis for Phase 2 of the project (reported here). As well, a more detailed review of geophysical tools which have not been tested in the western Canadian geological setting was recommended. This review was to determine which tools had the best chance of providing the desired parameters either directly or through simple correlations. Existing tools and those untested tools with the best chance of success will be field tested in Phase 3.

1.3 Objectives

1.3.1 Objectives of the Total Research Program

As outlined in the original proposals the objectives of the research program are to "... improve... and develop new techniques of using borehole geophysical data to determine geotechnical and hydrogeological characteristics of subsurface materials."

1.3.2 Objectives of Phase 2 (1987/1988)

The objective of Phase 2, conducted from April 1987 to March 1988, and reported here is "to evaluate the techniques identified in Phase 1 to obtain various geotechnical and hydrogeological parameters from downhole geophysics and to review which tools, not currently in use in Alberta, might have potential to provide the desired parameters."

The scope, objectives and methods of the subsequent phases will be modified to reflect the results and conclusions of the previous phases.

2. PROJECT APPROACH

2.1 Scope

The areas of interest for Phase 2 of this project were the correlations suggested in Phase 1 for which there were existing data which the project members could access. The availability of data, although known in general before Phase 2 started, was determined, in detail, as part of the work plan. The data collection and the correlations attempted are described in the technical chapters of this report.

2.2 Work Plan

The work plan generally follows the concept outlined in the original project proposals. The detailed work plan was generated at a project meeting held in conjunction with the expert panel to review the results of Phase 1 of the project. The revisions to the work plan were made to better reflect the results of Phase 1 and to recognize the limitations of data availability which were already apparent. This revised work plan is shown in Figure 1.

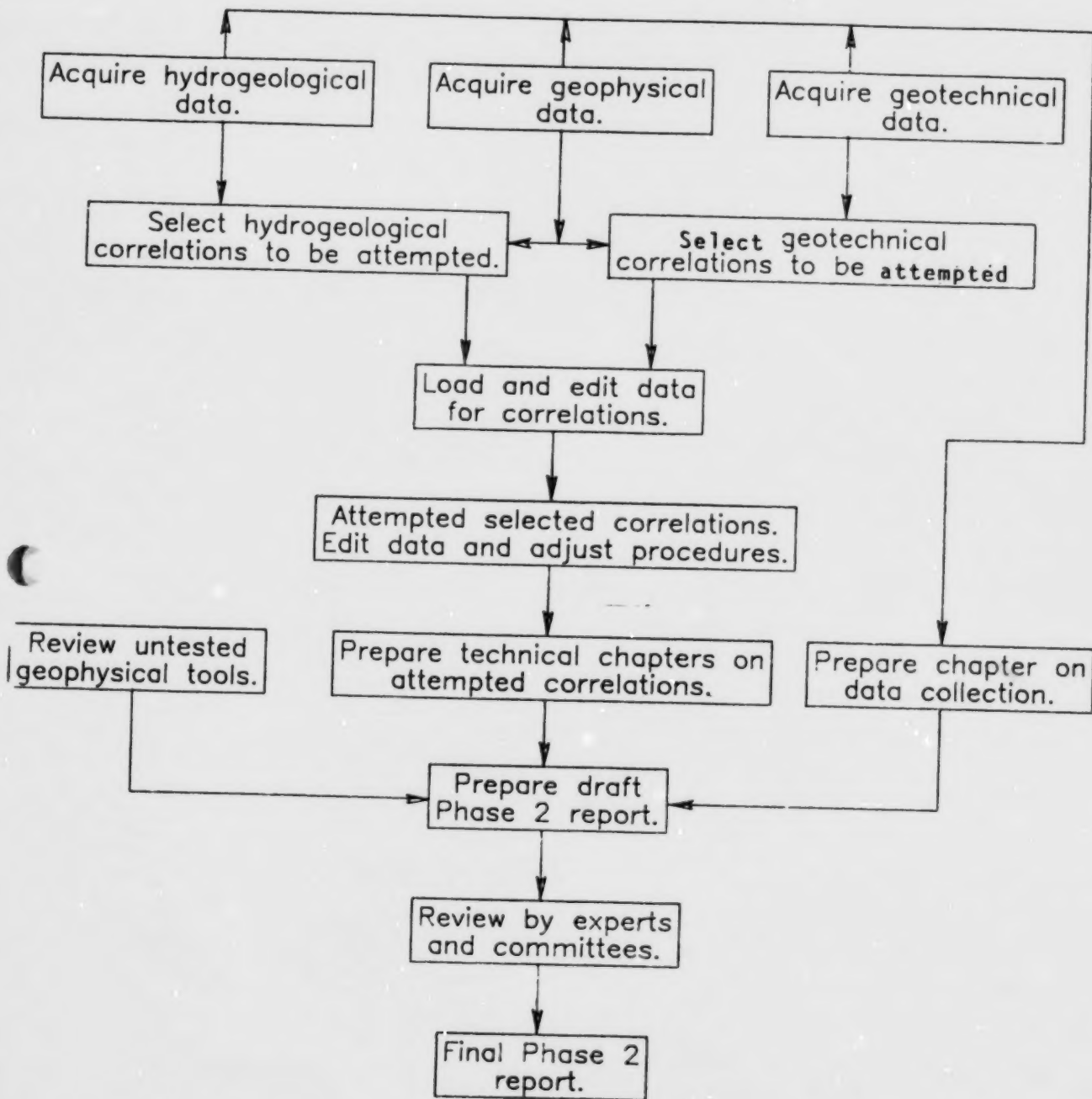
The data collection commenced by examining the participants' available data sets and selecting the matching geophysical and geotechnical or hydrogeological data for distribution to the groups working on the various correlations. The data was then loaded into a computer based manipulation system to allow the researchers to attempt the various suggested correlations. These correlations required, in some cases, editing and adjusting of the data to effect correct depth and composite relationships.

A review of the data collection procedures and the problems encountered is included in this report as well as a review of the correlations attempted and the procedures used.

As a preparation for the expected Phase 3 of the project, a detailed review of geophysical tools which have not been proven in the western Canadian plains environment was conducted. The objective of this review was to recommend which untested tools had the best chance of success in providing, either directly or by simple correlations, some of the geotechnical or hydrogeological parameters of interest. This review and associated recommendations are also included in this report.

The various reports, reviews and recommendations were collected and distributed as a rough draft report to the project members. The resulting revisions and comments were taken into account

DOWNHOLE GEOPHYSICS PROJECT LOGIC DIAGRAM



Phase 2 Work-Plan

FIGURE 1

and resulted in this single report of Phase 2 of the Downhole Geophysics Project.

2.3 Data Sources

Early in the review of existing information, it was apparent that there was an extensive collection of geophysical data and test results available. These data were scattered between various coal and oil sands companies and several government organizations. The job of collecting, organizing, reviewing and distributing all this data in a consistent format was clearly beyond the scope of this project. It was agreed by the management committee to limit the data search to those organizations participating in the project and to choose at least one data set for coal formations and one for the oil sands formations.

The data search took several stages. First the participants were asked to provide a rough estimate of the number of boreholes which had been geophysically logged and had at least some geotechnical or hydrogeological tests. The participants responded either formally or informally. From this survey, those companies or data sources with the widest variety of geophysical tools and geotechnical testing were chosen to provide the data to the Project.

TransAlta was chosen as one of the geotechnical data sources in part because of its large computer data base and because of its coal mining experience in the Western Plains geologic conditions. Highvale Mine was chosen to provide geophysical and geotechnical data as a representative of the coal industry. The Alberta Research Council (ARC) was chosen as a source of hydrogeologic data because of its expertise and varied work experience in the province. Syncrude was chosen as representative of oil sands mining operations that could provide good quality data from a select drilling program. The locations of the three chosen data sources are shown on the following map as Figure 2. A concerted but unsuccessful attempt was made to obtain data from the Alberta Oil Sands Technology and Research Authority (AOSTRA) underground test facility project in time for inclusion into the Project.

Subsequently, the selected data contributors needed to identify the number and type of tests available with what specific geophysical logs. Furthermore, it was useful to segregate this data into groups according to rock types where possible to determine whether correlations could be made for all rock types. For example, would there be sufficient number of compressive strength tests to allow development of a correlation curve covering a wide assortment of rock types?

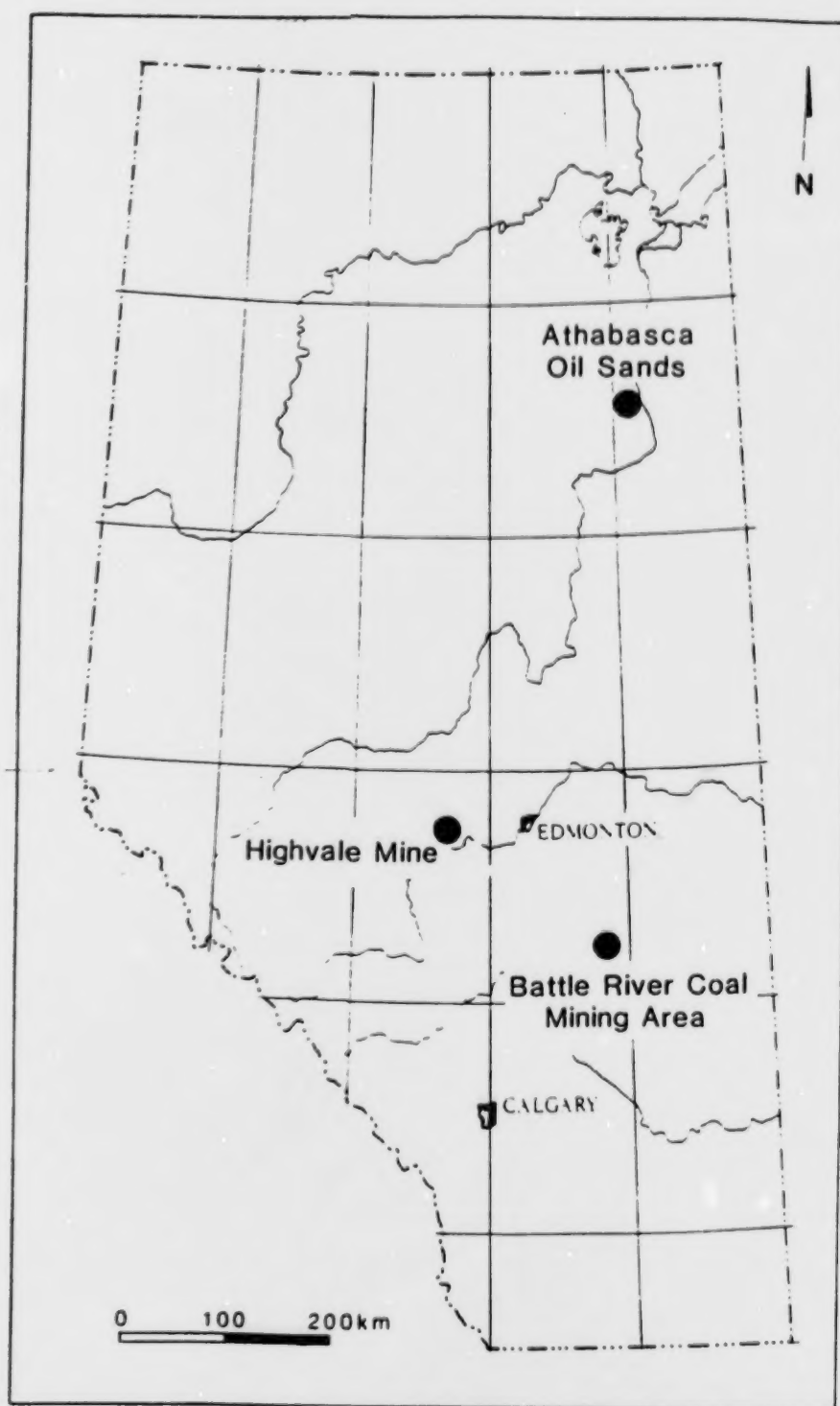


Figure 2 Location of data sources, Highvale Coal Mine, Battle River Coal Mining area and Athabasca Oil Sands area.

As originally envisioned, data were to be collated under one data base so that the data could be independently assessed by several investigators. However, overcoming the problems in electronically transferring data from varying computer system types, makes and formatting would require considerable effort. Further, not all the data was in electronic form. It was decided that it would be more efficient to evaluate each data set separately. This method also had the added benefit of ensuring the confidentiality of data.

A detailed description of the data sets for the two geotechnical and one hydrogeological evaluation are included with the relevant sections of this report.

2.4 Geological Settings

The Alberta coal and oil sands deposits lie within poorly lithified clastic sediments that were deposited in deltaic, fluvial and estuarine environments during Jura-Cretaceous and younger times. The sediments are characterized by variations in lithology, both horizontally and vertically, over very short distances, so that it is often difficult to correlate rock types, geotechnical characteristics, hydrogeological parameters, etc. without closely spaced drilling.

In addition to their stratigraphic complexity, the deposits have received varying degrees of tectonic deformation. The deposits of the Foothills and Mountain regions are strongly deformed, and are characterized by folds, a variety of types of faults, sheared zones, and joints. The Plains deposits (including oil sands) exhibit less faulting and little folding, but are jointed and in some areas have suffered glaciotectionic deformations, thereby contributing to their inherent weakness.

The TransAlta coal data is taken from the Highvale Mine area which is part of the Ardley coal zone. The hydrogeological data used by the Alberta Research Council were collected from coal exploration drilling in the Battle River area east of Red Deer. To better illustrate the general stratigraphy in the areas of selected data, typical stratigraphic columns are presented for the Athabasca Oil Sands and the Highvale and Battle River areas on Figures 3 and 4.

All of the information for the oil sands geotechnical work was provided by Syncrude from drilling and testing on their current leases in the McMurray Formation near Ft. McMurray. The data are from the Lower Cretaceous Clearwater Formation, a marine deposit that has been heavily over-consolidated. The Clearwater Formation consists of clays, silts and some sands which were deposited in a shallow epicontinental sea approximately ninety million years ago. The Clearwater Formation comprises the bulk of the overburden deposits on the two leases with the exception of a thin veneer of glacial sediments which average five to seven metres in thickness. A schematic cross section of the Syncrude Lease is shown on Figure 5.

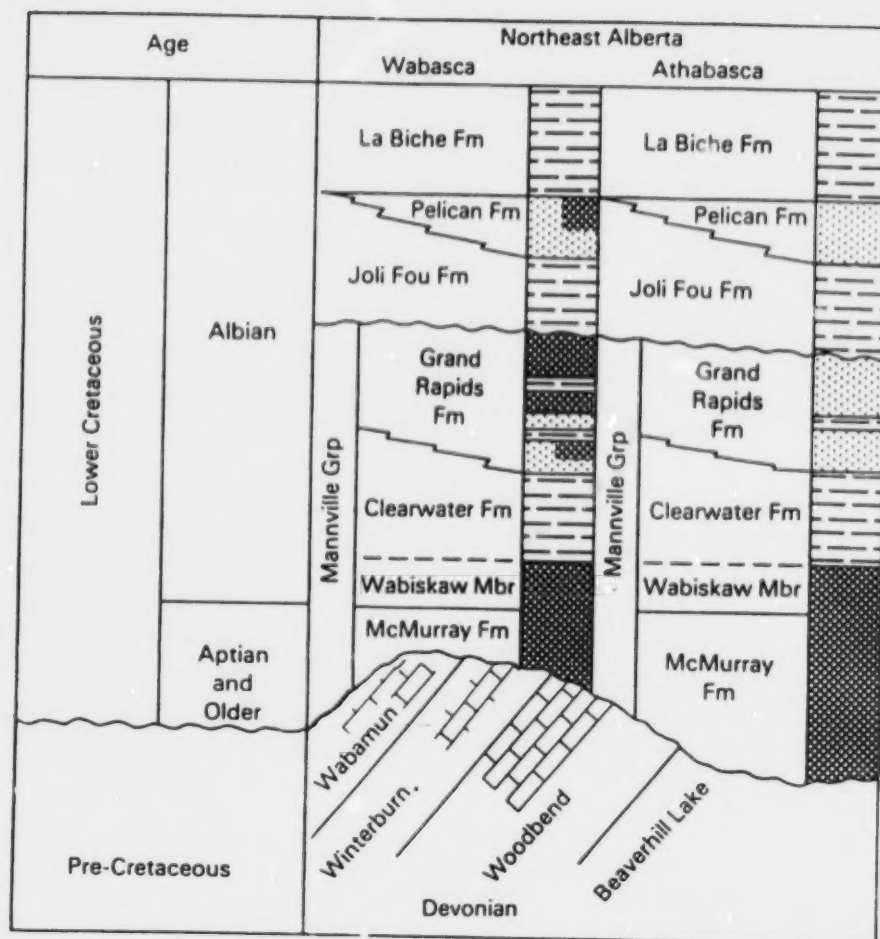


Figure 3. Stratigraphy of Athabasca Oil Sands area (modified from Kramers and Mossop, 1987).

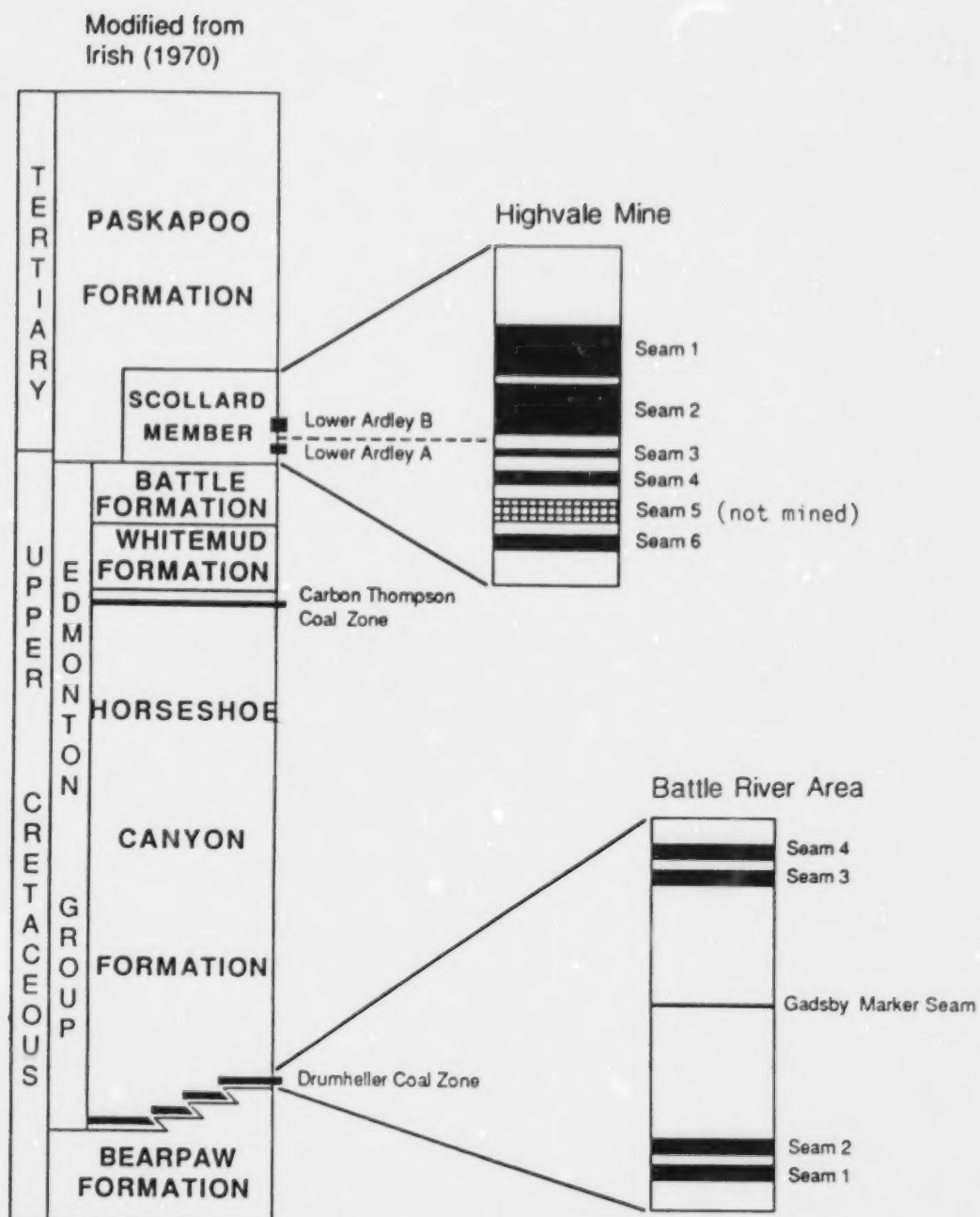
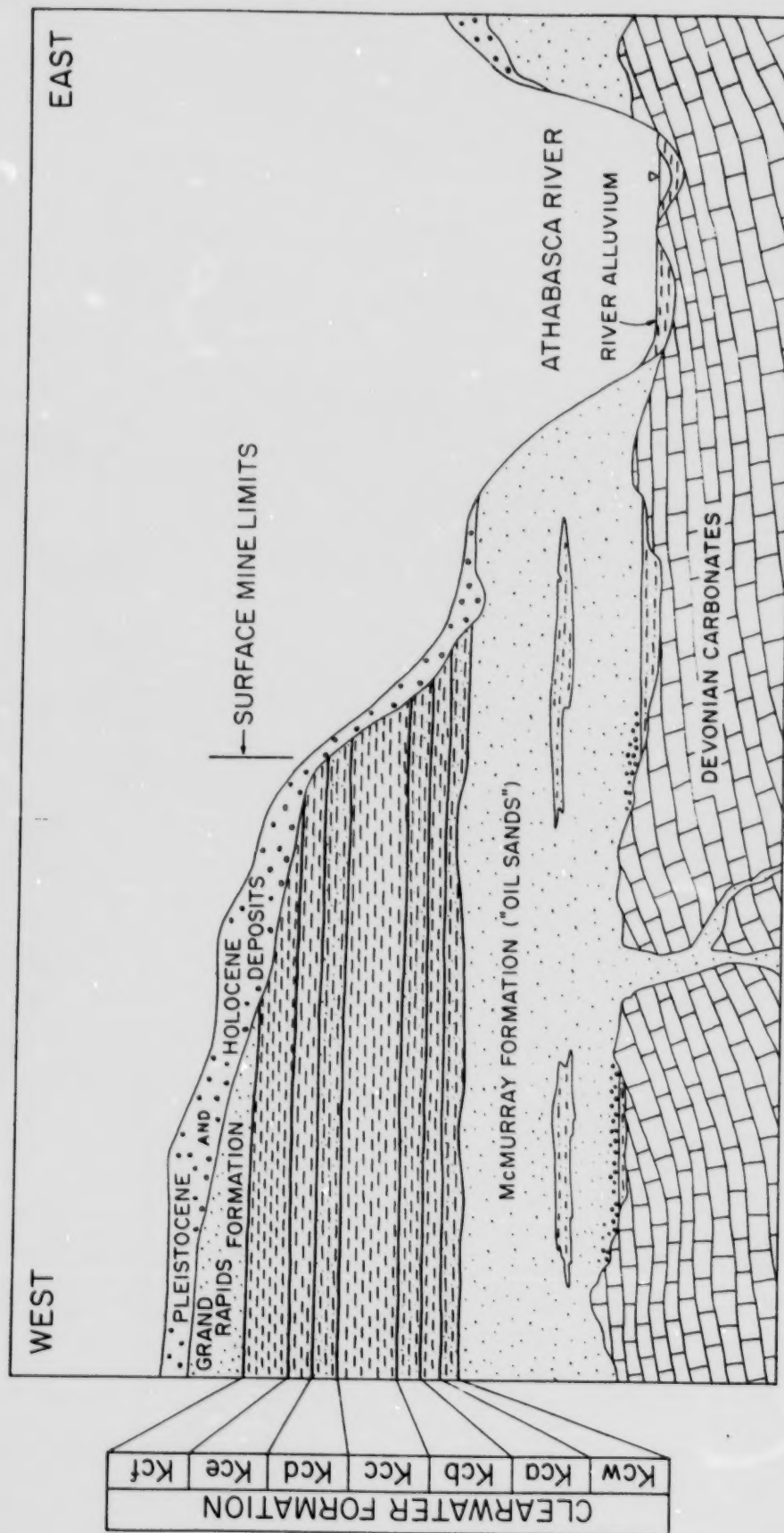


Figure 4. Stratigraphy of Highvale and Battle River areas.



SCHEMATIC CROSS-SECTION
SYNCRUDE CANADA LTD. LEASES

FIGURE 5

3. GEOTECHNICAL - COAL FORMATIONS

3.1 Data Search

In TransAlta's experience, electronic data base manipulation was more cumbersome than expected. The time expended in learning to retrieve data was a result of having more experience in storing data than retrieving it. This is a common problem since data entry is a repetitive, labour intensive effort where as data requests can be quite varied and often unique.

An example of the kind of problems encountered was the difficulty in retrieving geotechnical data by lithology type. This was because searching by lithology is done through the geologic log rather than through the description of the sample taken for geotechnical testing. Because the geotechnical sample interval is usually much smaller than the geological interval, often the geologic description differs from the geotechnical description. This problem was resolved but entailed manual sorting of data.

These and other problems arose mainly from the structure of the data base. This is not surprising since it would have been difficult at the time the data base was set up to envision the connection between geotechnical, geophysical and geological data.

Retrieval of geophysical logs alone was efficiently done through a log analysis program called Terralog. Despite little experience with this program, data were easily retrieved through a menu-driven program and transferred to a PC computer for data analysis.

Unfortunately, older geophysical data were not in good order and many tapes could not be read due to procedure and equipment changes over the years. For example, the older tapes needed to be reformatted from the older 800 bits per inch (bpi) format to the newer 1,600 bpi. As well, 10 cm reading spacing were changed to 1 cm spacing for greater detail. While these problems were easily resolved, it did cause delays and subsequently some data were not available at the time of data analysis. Geophysical data collected in recent years are in good shape probably because of the increased use of geophysics in identifying lithology.

Initial data base queries revealed that there were some 877 boreholes. These boreholes which were located in the Highvale Mine, the Whitewood Mine and the Low Water Lake area; containing varying degrees of geotechnical and geophysical data. Due to time constraints and formatting problems with early geophysical data, only 1982 and subsequent data from Highvale Mine was used in this study.

Geotechnical data were retrieved from the TransAlta geotechnical data set and the suite of geophysical logs, corresponding to the same lithology and stratum depth interval as the geotechnical test specimens, obtained from the Terralog tapes at TransAlta.

3.2 Methodology

The geotechnical and geophysical data were supplied by TransAlta on floppy discs in the Lotus 1-2-3 format and on hard copy. Monenco rearranged these data to create a series of files containing drillhole number, depth interval, material type, selected geotechnical parameters and corresponding geophysical log values. Statistical regression analyses were utilized to characterize the relationships between individual geotechnical parameters and the geophysical log values corresponding to the same stratum depth interval. Geotechnical parameters selected were:

- . uniaxial compressive strength
- . natural moisture content (based on oven-dry weight)
- . liquid and plastic limits
- . bulk density

Geophysical log data were supplied in digitized format at 1 cm depth intervals and included the following logs:

- . Gamma
- . Density
- . Resistivity
- . Neutron
- . Sonic
- . Caliper

The Lotus 1-2-3 statistical, and XY graphics packages were used in the data pairing procedures. In addition, the statistical method of regression analysis for obtaining the best-fit polynomial equation was conducted manually for correlating the uniaxial compressive strength with sonic transit time to obtain a higher correlation coefficient than was possible with the Lotus package. The correlations obtained by these procedures are primarily empirical since no attempt was made to establish a theoretical basis for the relationships.

In carrying out the correlations, it was found that the scatter of plotted data was significantly reduced when the procedures outlined in the following were adopted.

3.2.1 Qu vs Sonic Transit Time

To avoid excessive data scatter and obtain the best correlations between the uniaxial compressive strength, Q_u , and sonic transit time, the following procedure was established:

- . Adjust the depth interval location, where necessary, of the uniaxial compression test results to agree with the lithology depth interval determined from geophysical logs.

- . Use the average value of the sonic log spacing signature (Channel 3 on the BPB probe) over the stratum thickness being considered. Minimum acceptable stratum thickness = 1.5 times Channel 3 receiver spacing.
- . Use digitized sonic transit time readings at 1 cm intervals of borehole depth.
- . Do not use sonic data if the borehole diameter varies as denoted by the caliper log by more than 0.1 inch over the depth interval considered.
- . Do not use sonic data if any of the three sonic log (short, medium and long) values remain constant over the depth interval.

3.2.2 All Other Correlations

Once each spreadsheet file containing the geotechnical parameter(s) being considered and the corresponding geophysical log(s) was set up from the base data, the file was condensed to eliminate rows containing missing data. Thus only those geotechnical data values which corresponded to a complete suite of geophysical logs were used for establishing the correlations.

3.3 Tools and Tests

The type of geotechnical tests commonly conducted range from triaxial compression tests to Atterberg Limits as indicated in Table 1. All testing conformed to ASTM standards except when laboratories were instructed to deviate from the prescribed ASTM procedures, as for example, when the samples are blenderized in preparation for the Atterberg Limits test.

Table 1

LIST OF GEOTECHNICAL TESTS

<u>Geotechnical Test</u>	<u>Properties</u>
Moisture Content	moisture, degree of saturation
Atterberg Limits	plasticity
Consolidated Undrained Triaxial	shear strength
Unconsolidated Undrained Triaxial	compressive strength
Direct Shear	shear strength
Bulk Density	weight
Grain Size	particle size variation
Pocket Penetrometer	strength, density, consistency
Vane	strength, density, consistency
Cone Penetrometer	strength, density, consistency
Standard Penetration Test	strength, density, consistency

Both Century Geophysical Corporation and BPB Instruments Ltd. have been used in the past to log the boreholes. The data used in this report, with few exceptions, has been provided by BPB tools which are listed in Appendix II.

Typical log response ranges for each tool and rock type found at the Highvale Mine are presented in Figure 6.

3.4 Correlations

A summary of the correlations established between geotechnical and geophysical parameters is given in Table 2 and a list of the geophysical log cross-plots obtained is shown in Table 3. Also included in each table are the respective correlation coefficients and number of observations for each relationship. Graphs depicting the more promising correlations are included in Appendix III.

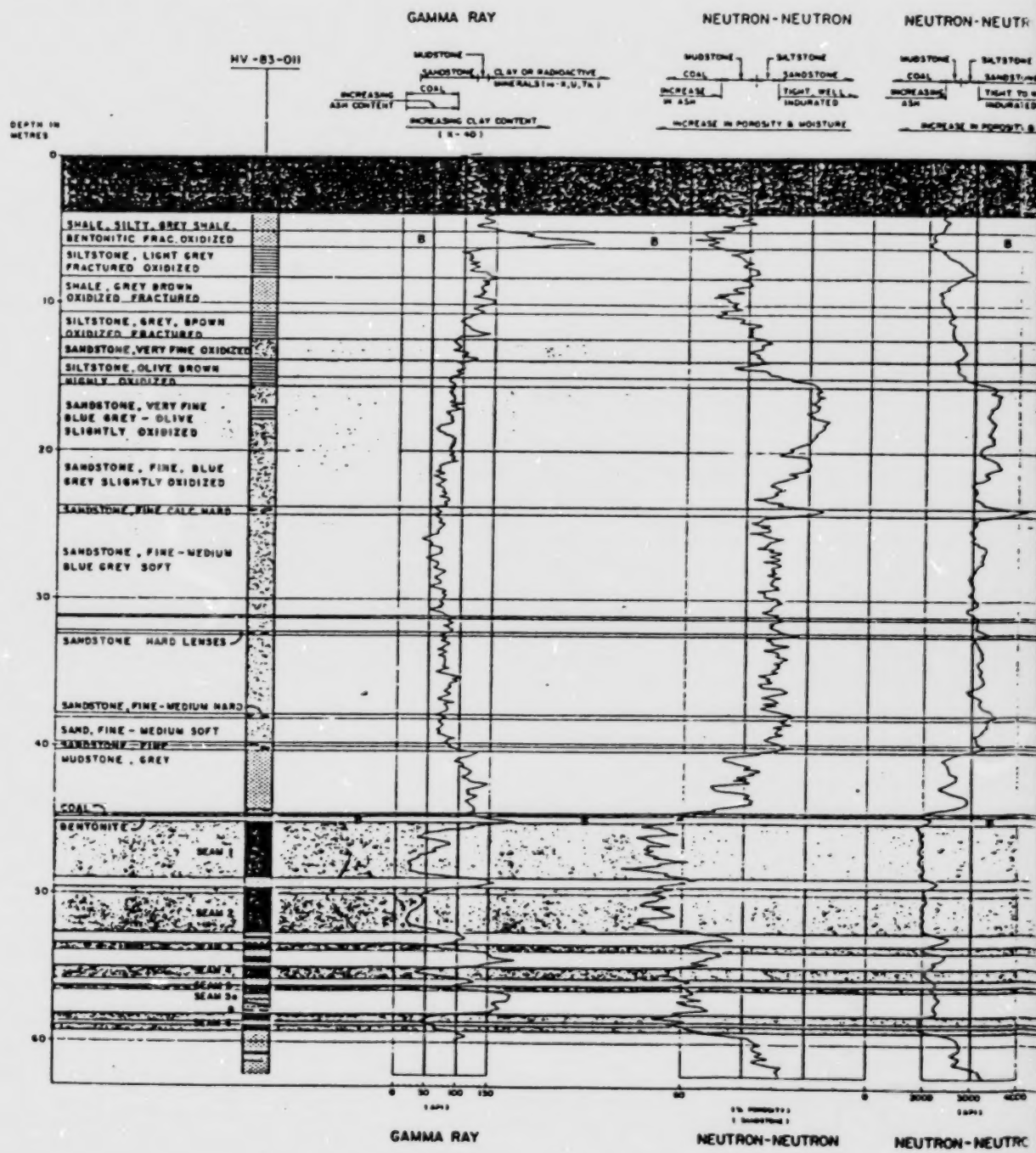
Each of the correlations and cross-plots included symbols for the main overburden lithological units which are comprised of sandstone, siltstone, mudstone and bentonite. Due to time constraints, however, no attempt was made to develop correlations for individual lithologies.

In addition, parameters for glacial till, which mantles the Highvale area to an average depth of about 5 m, were not correlated.

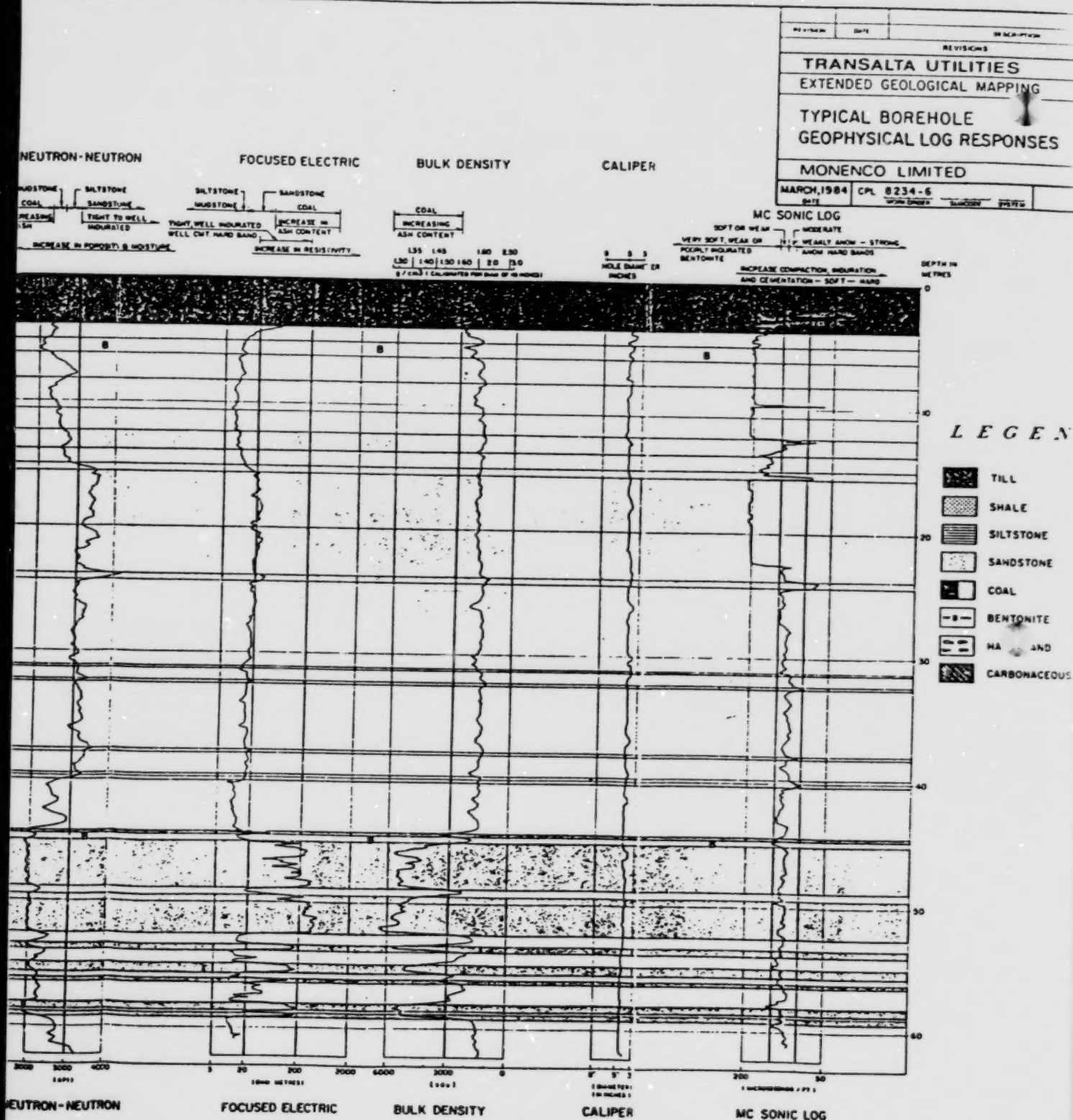
3.5 Discussion

Apart from the procedures outlined in Section 3.2, no attempt was made to evaluate and cull the data to generate optimal correlations. Most of the correlations were developed using linear regression analyses but, as indicated for the Qu vs Long Sonic relationship in Table 2, it may also be possible to upgrade correlations for some data pairs by fitting polynomial curves rather than straight lines to the plotted data. This is illustrated in Figure 7 which shows plots of Sonic Travel Time against uniaxial compressive strength.

It is probable, however, that the equations shown in Tables 2 and 3 would change if the number of observations were substantially increased. Furthermore, it is not known to what extent the relations obtained are site specific since comparison of the Highvale data with data from other sites was not done.



A SUITE OF LOGS RUN TO SHOW TYPICAL RESPONSE C



RESPONSE OF SPECIFIC LOGS TO VARIOUS LITHOLOGIES AND ROCK CONDITIONS

FIGURE 6

TABLE 2
Highvale Mine - Summary of Satisfactory Correlations

Parameters Correlated	Equations Obtained	R	N
WC vs Gamma	$WC = 0.234 (\text{Gamma}) - 8.284$	0.72	81
WC vs Density Log	$WC = 141.86 - 57.0 (\text{DenLog})$	0.86	81
	$WC = \log^{-1} [5.77 - 2.12 (\text{DenLog})]$	0.87	81
WC vs Neutron	$WC = 58.65 - 0.0192 (\text{Neut})$	0.80	81
	$WC = 367.19 - 105.1 \log(\text{Neut})$	0.82	81
	$WC = 4.73 \times 10^{14} (\text{Neut})^{4.065}$	0.86	81
	$WC = \log^{-1} [2.80 - 0.00076 (\text{Neut})]$	0.87	81
WC vs Long Sonic	$WC = 0.08 (\text{Sonic}) - 20.58$	0.66	81
WC vs Resistivity	$WC = 22.73 - 0.52 (\text{Resist})$	0.58	81
Bulk Density vs Gamma	$\text{BDen} = 2634 - 3.81 (\text{Gamma})$	0.60	94
	$\text{BDen} = 4727 (\text{Gamma})^{-0.164}$	0.59	94
Bulk Density vs Neutron	$\text{BDen} = 1370 + 0.388 (\text{Neut})$	0.79	94
	$\text{BDen} = 104.1 (\text{Neut})^{0.4}$	0.78	94
	$\text{BDen} = 2076 \log(\text{Neut}) - 4704$	0.79	94
	$\text{BDen} = \log^{-1} [3.182 + 0.000074 (\text{Neut})]$	0.78	94
Bulk Density vs Long Sonic	$\text{BDen} = 3023 - 1.76 (\text{Sonic})$	0.69	94
	$\text{BDen} = 1.55 \times 10^4 (\text{Sonic})^{-0.32}$	0.69	94
Bulk Density vs Resistivity	$\text{BDen} = 2076 + 11.2 (\text{Resist})$	0.59	94
	$\text{BDen} = 1728 (\text{Resist})^{0.10}$	0.65	94
Bulk Density vs Density Log	$\text{BDen} = 1190 (\text{DenLog}) - 403$	0.84	108
Qu vs Neutron	$Qu = 0.038 (\text{Neut}) - 79.8$	0.69	58
	$Qu = 248 \log(\text{Neut}) - 827$	0.71	58
	$Qu = 1.5 \times 10^{-28} (\text{Neut})^{8.4}$	0.68	58
Qu vs (Neutron x Density Log)	$Qu = 0.02 (\text{Neut} \times \text{DenLog}) - 85.6$	0.78	58
	$Qu = \log^{-1} [6.2 (\text{Neut} \times \text{DenLog}) - 13.7]$	0.85	58
	$Qu = 6.3 \times 10^{-29} (\text{Neut} \times \text{DenLog})^{7.7}$	0.77	58
Qu vs Long Sonic	$Qu = 224 - 0.82 (\text{Sonic}) + 0.00073 (\text{Sonic})^2$	0.91	58
	$Qu = \log^{-1} (3.73 - 0.0075 (\text{Sonic}))$	0.80	58

Legend:

WC	= Natural moisture content, %
DenLog	= Density Log, Mg/c.m.
Bulk Density	= In situ density from laboratory test, kg/c.m.
Sonic	= Average Long Sonic Transit Time, micro-sec/m
Qu	= Uniaxial compressive strength, MPa
R	= coefficient of correlation
N	= no. of observations

TABLE 3

Highvale Mine - Summary of Geophysical Parameter Cross-Plots

Parameters Correlated	Equations Obtained	R	N
Density Log & Neutron	Neut = 2166 (DenLog) - 2554 Neut = $\log^{-1} [0.416 (\text{DenLog}) + 2.42]$	0.82 0.84	105 105
Density Log & Gamma	Gamma = 403.5 - 136.6 (DenLog)	0.66	105
Density Log & Long Sonic	Sonic = 1184 - 337 (DenLog) Sonic = $\log^{-1} [3.435 - 0.36 (\text{DenLog})]$ Sonic = 1734 (DenLog) - 1.76 Sonic = 1003 - 1642 log(DenLog)	0.68 0.68 0.66 0.66	105 105 105 105
Density Log & Resistivity	Resist = 32.6 (DenLog) - 56.2 Resist = $\log^{-1} [0.81 (\text{DenLog}) - 0.66]$ Resist = 0.62 (DenLog) 3.89 Resist = 157 log(DenLog) - 38	0.49 0.50 0.48 0.47	105 105 105 105
Resistivity & Neutron	Neut = 1769 + 30.9 (Resist) Neut = 1202 (Resist) 0.24 Neut = 813 + 1282 log(Resist)	0.78 0.78 0.79	105 105 105
Resistivity & Gamma	Gamma = 131 - 2.0 (Resist)	0.63	105
Neutron & Gamma	Neut = 3284.5 - 10.17 (Gamma) Neut = 1.72 x 10 ⁴ (Gamma) - 0.45	0.80 0.84	105 105
Long Sonic & Neutron	Sonic = 1.78 x 10 ⁵ (Neut) - 0.78	0.73	105
Long Sonic & Resistivity	Sonic = 7.2 x 10 ² (Resist) - 0.2	0.62	105

For Legend see Table 2

To evaluate individual relationships paired, correlations were tentatively classified according to the R value obtained from the regression analysis as follows:

<u>R Value</u>	<u>Correlation Rating</u>
0.9+	very good
0.8 - 0.9	good
0.7 - 0.8	fair
0.6 - 0.7	poor
less than 0.6	unsatisfactory

The relationships in Table 2 which exhibit R values greater than 0.8 are deemed potentially useful in determining geotechnical parameters from the respective geophysical logs values. Those logs which appear most useful are the Neutron, Density and Sonic logs. With an R value of 0.87, the natural water content of a geologic formation can be predicted from the Neutron and Density logs by the following expressions:

$$\begin{aligned} WC &= \log^{-1} [5.77 - 2.12 (\text{DENLOG})] && \dots\dots\dots(1) \\ WC &= \log^{-1} [2.80 - 0.00076 (\text{NEUT})] && \dots\dots\dots(2) \end{aligned}$$

Similarly, expressions for the Bulk Density ($R = 0.84$) and uniaxial compressive strength ($R = 0.85$ to 0.91) are as follows:

$$\begin{aligned} \text{Bulk Density} &= 1190 (\text{DENLOG}) - 403 && \dots\dots\dots(3) \\ Qu &= 224 - 0.82(\text{SONIC}) + 0.00073(\text{SONIC})^2 && \dots\dots\dots(4) \\ Qu &= \log^{-1} [6.2 (\text{NEUT} \times \text{DENLOG}) - 13.7] && \dots\dots\dots(5) \end{aligned}$$

Attempts to relate various Atterberg Limits test parameters to geophysical log values were thus notably unsuccessful as illustrated in Table 4. Correlations involving the Liquid Limit (LL), Plasticity Index (PI) and Relative Consistency (Cr) all exhibited correlation coefficients (R) less than 0.60.

A foreknowledge of the above geotechnical parameters from a feasibility exploration in which only geophysical logging of the drill holes is carried out would be useful in selecting the best locations for geotechnical core sampling in subsequent drilling programs. Noncarbonaceous formations with high natural moisture or low density are indicative of weak materials which may jeopardize the stability of pitwall slopes or give rise to trafficability problems.

By relating sonic transit time of a given formation to the corresponding uniaxial compressive strengths, valuable information on the diggability characteristics of the overburden units can be obtained over a wide area of the mine. Practical use of this correlation is being considered (A. Hickinbotham, Personal Communications) to assess diggability in the selection of mining equipment for planning purposes. To determine whether universal relationships exist between selected geotechnical and geophysical parameters, or to improve specific correlations for a given site, it will be necessary to carry out further studies. Based on the work conducted on the Highvale data to date, it appears that better correlations may be realized if the following procedures are used:

TABLE 4

Highvale Mine - Unsatisfactory Correlations

Parameters Correlated	R	N
LL vs Gamma	0.42	52
LL vs logGamma	0.40	52
log LL vs Gamma	0.42	52
LL vs Neutron	0.31	52
LL vs logNeutron	0.30	52
logLL vs logNeutron	0.37	52
logLL vs Neutron	0.38	52
LL vs Density Log	0.59	52
LL vs logDensity Log	0.60	52
logLL vs Density Log	0.58	52
logLL vs logDensity Log	0.58	52
LL vs Long Sonic	0.07	52
LL vs Resistivity	0.03	52
PI vs logDensity Log	0.58	52
PI vs logNeutron	0.27	52
PI vs logGamma	0.37	52
PI vs Density Log	0.57	52
PI vs Neutron	0.28	52
PI vs Gamma	0.39	52
Cr vs Gamma	0.29	28
Cr vs Density Log	0.29	28
Cr vs Neutron	0.44	28
Cr vs Sonic	0.18	28
Cr vs Resistivity	0.34	28

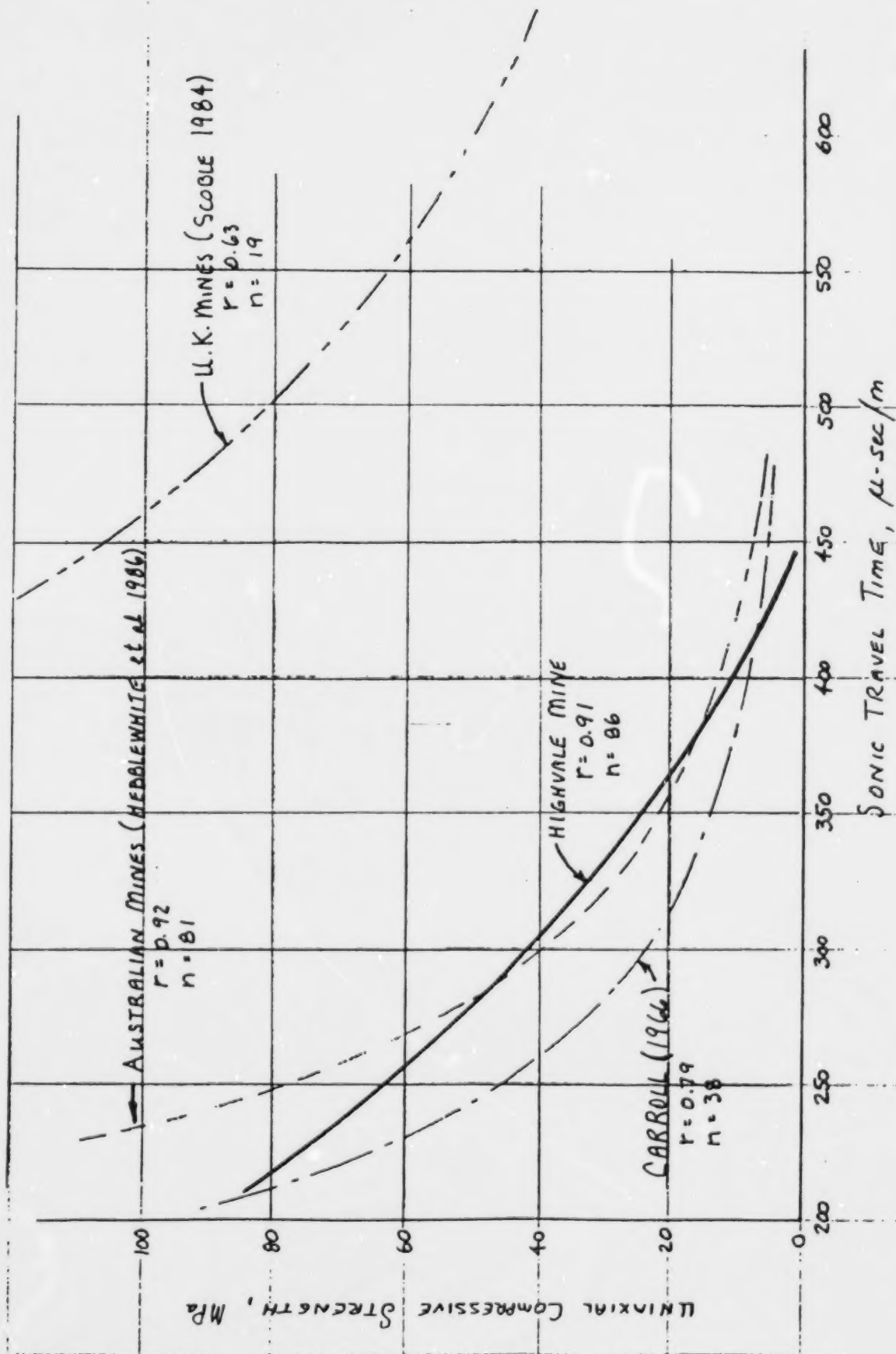
Legend:

LL = liquid limit, %
 Cr = relative consistency = $(LL - W) / PI$
 W = water content, %
 PI = plasticity index, %
 Sonic = avg. long sonic transit time, micro-sec/m

Note:

All geophysical log values used were average values over the stratum thickness being considered.

- Pair combinations of parameters to enhance the correlation coefficient, e.g. from Table 2, Qu vs Neutron gives maximum $R = 0.71$ whereas Qu vs (Neutron x Density Log) increases R to 0.85.
- Include data from different sites in the parameter pairing, e.g. the Qu vs Sonic Travel Time relationship for Highvale data is comparable to that for Australian Mines (see Figure 7). Care must be taken to minimize the errors due to different equipment and calibration before incorporating the data.
- Evaluate individual lithologic units separately and possibly group according to depth to ascertain effects of glaciation.
- By conducting appropriate analyses, determine the minimum number of observations required to ensure a given relationship is statistically significant, or conversely, establish the minimum acceptable coefficient of correlation required to adequately define a reliable correlation.



4. GEOTECHNICAL - OIL SANDS FORMATIONS

4.1 Data Search

The data compiled in this section of the study were from Syncrude Canada Ltd's two oil sands leases 17 and 22, located in the Athabasca Oil Sands area of Northeastern Alberta.

The data were selected after reviewing geotechnical and geophysical information that existed in different files or departments of the Syncrude organization. Much of these data were in hard copy form which could not be easily incorporated into this study.

Two groups of geotechnical and geophysical data were selected. These are designated as:

- (1) Grainsize 01 to 21
- (2) Holes 01 to 12.

4.2 Methodology

In the First Group Data file, geophysical log values were compared to the grain size fraction. These were both downloaded from a mainframe data base onto a personal computer Lotus 1-2-3 spreadsheet file. The geophysical logs were digitized at ten centimetre intervals.

In the Second Group Data file, the geophysical log values were also downloaded from a mainframe data base onto a personal computer Lotus 1-2-3 spreadsheet file. The geotechnical test intervals were manually entered into the Lotus file at the correct depths. In the case of the resistivity, density, and neutron logs some test interval depths were corrected. This type of correction occurred when the test interval was located near a lithologic contact resulting in large changes in geophysical log values. Because of limits to the resolution capability of tools, the geophysical response is gradational, increasing as the contact is approached. Thus, geophysical response values close to such a contact are not representative of either lithologic type and have been eliminated.

The geotechnical and geophysical data were supplied by Syncrude on floppy discs in the Lotus 1-2-3 format. Terracon rearranged these data to create a series of files. Each file contained hole number, measurement depth, one geophysical log and one geotechnical parameter. A number of successive files were created and each geotechnical parameter was paired with the appropriate log parameter.

The statistical regressions employed the following geotechnical parameters: undrained shear strength, liquid limit, plasticity index, moisture content and grain size data. The geophysical log data were supplied in digitized format and included data from the gamma, density, resistivity and neutron logs.

Certain data populations were sufficiently large to subdivide the correlation fields into sub-units of the Clearwater Formation. From eldest to youngest these members have been designated as Kcw, Kca, Kcb and Kcc.

The grain size data were examined on the basis of four separate properties, namely: sand content, silt content, fines content and the slope of the grain size gradation curves. This slope was derived by subtracting the amount of material passing through the 2.8 micron sieve from the amount of material passing through the 62 micron sieve and dividing by the sieve size difference (59.2 microns). The geophysical parameters include gamma, resistivity, neutron-porosity and density-porosity.

4.3 Tests and Tools

The First Group of data were obtained from 21 core holes (GR 01 to 21) drilled with a rotary diamond drill rig using an HQ wireline core barrel.

Two hundred and nineteen grain size tests were completed in 21 core holes. The grain size data were analyzed using a Microtrac test instrument. Microtrac sizes which were recorded are: 150, 125, 88, 62, 44, 31, 22, 16, 11, 7.8, 5.5, 3.9, and 2.8 Microns. Of the two hundred and nineteen samples only three or four contained coarser fractions with a grain size greater than one hundred and fifty microns. The coarser fraction was not analyzed.

The Second Group of data were selected from different drilling programs covering the period between February 1975 and December 1985. Samples for geotechnical tests from Hole 01 were obtained with a rotary rig using an HQ wireline core barrel. The remaining holes were drilled with a rotary rig using a Pitcher Barrel sampler and Shelby tubes. The testing completed in the twelve holes (Holes 01 to 12) is summarized in Table 5 and particulars of some of the tests are included below:

- . Moisture Content ASTM D2216-71.
- . Atterberg Limits, samples prepared with five minutes of blenderizing and one hour rest before testing, ASTM D2216-71.
- . Clay Mineralogy (Montmorillonite, Chlorite, Illite and Kaolinite), the X-Ray Diffraction tests were performed with glyconated samples at the Alberta Research Council.

GEOTECHNICAL TESTING
(HOLE 01 TO HOLE 12)

[illegible]

- Grain Size - the total percentage of clay, silt, and sand were reported using the Quick Hydro Meter Tests. ASTM procedures were followed with the exception that a three per cent solution of H_2O_2 (hydrogen peroxide) was used to soak the sample until fizzing has stopped. The sample was then blenderized for two minutes then added to 125 ml of a four per cent solution of Calgon. The remaining liquid volume for the hydrometer test was made up using distilled water.
- Unconfined compressive strength ASTM D2166-66.

The geophysical logging for the First Group (Grain Size 01 to 21) was performed by GEOLOG CANADA LTD. and various contractors for the other 12 holes.

The geophysical logging tool specifications for the adjacent holes are summarized on Table 6. The geophysical signatures and lithologic characteristics of the Clearwater Formation are shown in Figure 8.

4.4 Correlations

A total of 55 correlation plots have been generated with the available data. These are listed in Table 7. These graphs include both linear and semi-logarithmic plots for each parametric pairing. The correlation graph plots are presented in Appendix IV.

4.5 Discussion

4.5.1 Moisture Content

The moisture content is the ratio of the weight of water to the weight of dry soil/rock. This parameter was correlated against three geophysical logs, Bulk Density, Neutron Porosity and Resistivity. Correlation coefficient values are summarized as follows.

<u>Log Type</u>	<u>Linear Plot</u>	<u>Semi-Logarithmic Plot</u>
Density	-0.77	-0.76
Neutron-Porosity	+0.52	--
Resistivity	+0.25	+0.26

The negative R values indicate inverse relationships. The results show that for these sediments a reasonable inverse correlation has been obtained for the moisture content density correlation curve and that moisture estimates made from density curve provide reasonable approximations of the moisture values.

HOLE 01 TO HOLE 12

TABLE 6
GEOPHYSICAL LOGGING TOOL SPECIFICATIONS

HOLE NUMBER	LOGGING COMPANY	DATE	GEOPHYSICAL LOGGING TOOL SPECIFICATIONS										
			SONDE	RESISTIVITY		GAMMA RAY		DENSITY		NEUTRON		CALIPER	
			SPEED	TC SEC	SONDE	SPEED	TC SEC	SONDE	SPEED	TC SEC	SONDE	SPEED	TC SEC
01	BPB	Dec/1985	232	9 0.3	118	9 1	0.3						
02	Schlumberger	Feb/1978	117	30 2	PGT CNT	30 2	PGT CNT	515	9 1	118	9 0.3		
			Laterolog-8					PGT CNT	30 2	PGT CNT	30 2		
03	Schlumberger	Feb/1977	192	30 2	PGT-E, CNT-A	30 2	PGT-E, CNT-A	30 2	PGT-E, CNT-A	30 2	PGT-E, CNT-A	30 2	
			Laterolog-8										
04	Schlumberger	Feb/1978	117	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	
			Laterolog-8										
05	Schlumberger	Feb/1978	117	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	
			Laterolog-8										
06	Dresser Atlas	Mar/1975	1300	20 3	1305	20 3	2208	20 3	-	-	-	20 3	
			Laterolog										
07	Schlumberger	Feb/1978	117	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	
			Laterolog-8										
08	Schlumberger	Feb/1978	117	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	
			Laterolog-8										
09	Schlumberger	Feb/1978	117	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	
			Laterolog-8										
10	Dresser Atlas	Feb/1975	LSL 1300	20 3	1305	20 3	2208	20 3	-	-	-	20 3	
			Induction										
11	Dresser Atlas	Feb/1975	LSL 1300	20 3	1305	20 3	2208	20 3	-	-	-	20 3	
			Induction										
12	Schlumberger	Jan/1978	117	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	PGT-H, CNT-A	30 2	
			Laterolog-8										

HOLES GR1 - 21

LOG

6' Normal Sodium Oxide 12 2 ; Focussed# 12 0.5 Thermal American Beryllium
 12- Crystal side Wall 12 1 Single Arm 12

*Compensated single detector

Table 7

GEOTECHNICAL-GEOPHYSICAL CORRELATIONS

<u>Parameters</u>	<u>R Coefficients</u>		<u>No. of Plots</u>
	<u>Linear</u>	<u>Semi Log</u>	
Moisture Content vs Bulk Density	.77	.76	2
Moisture Content vs Neutron Porosity	.23	.30	2
Moisture Content vs Resistivity Log	.25	.26	2
Undrained Shear Strength vs Gamma	.36	.51	2
Undrained Shear Strength vs Bulk Density	.59	.70	2
Liquid Limit vs Gamma	.03	.05	2
Liquid Limit vs Bulk Density	.48	.47	2
Plasticity Index vs Gamma Log (Kcw)	.70	.71	2
Plasticity Index vs Gamma Log (Kca)	.35	.27	2
Plasticity Index vs Gamma Log (Kcb)	.13	.11	2
Plasticity Index vs Gamma Log (Kcc)	.44	.48	2
Plasticity Index vs Bulk Density	.44	.44	2
Fines Content vs Resistivity	.02	.02	2
Fines Content vs Neutron Porosity	.48	.49	2
Fines Content vs Density Porosity	.11	.07	2
Fines Content vs Gamma	.47	.54	2
Silt Content vs Resistivity	.11	.11	2
Silt Content vs Neutron Porosity	.09	.11	2
Silt Content vs Density Porosity	.005	.018	2
Silt Content vs Gamma			2
Sand Content vs Resistivity	.10	.04	2
Sand Content vs Neutron Porosity	.30	.32	2
Sand Content vs Density Porosity	.05	.03	2
Sand Content vs Gamma	.72	.72	2
Gradation Curve Slope vs Resistivity	.11	.13	2
Gradation Curve Slope vs Neutron Porosity	.09	.11	2
Gradation Curve Slope vs Density Porosity	.005	.018	2
Gradation Curve Slope vs Gamma	.62	.62	2
Total			56

GEOPHYSICAL SIGNATURES AND LITHOLOGIC CHARACTERISTICS OF THE CLEARWATER FORMATION

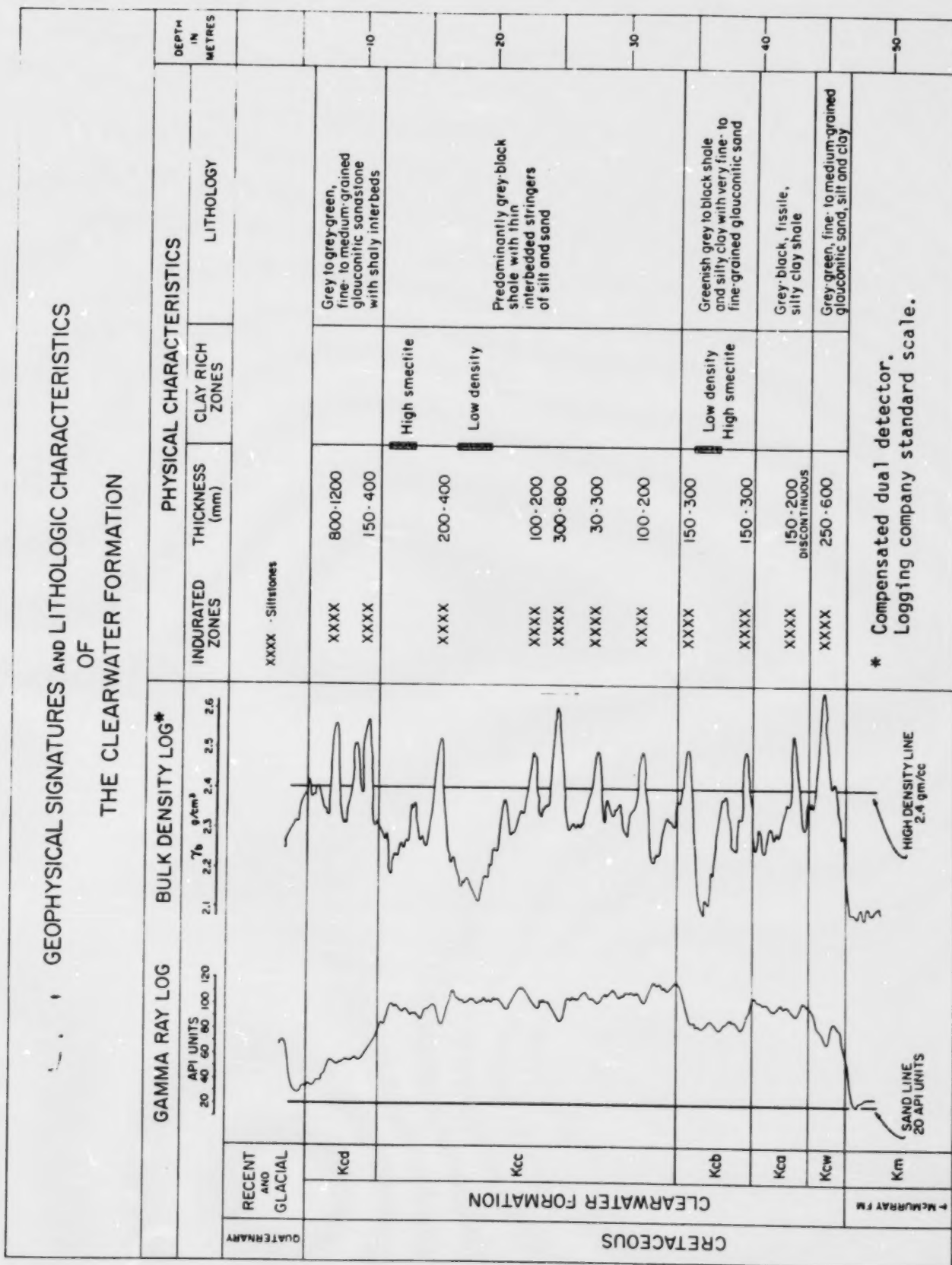


FIGURE 8

The other R values are insufficiently strong to warrant further correlation attempts. The neutron-porosity log is affected by mineralogy, bitumen content (not generally present in the Clearwater Formation except in Kcw) and dissolved solids in the pore water as well as the amount of pore water. Consequently, the correlation is poor. The resistivity plot is affected by the dissolved solids content of the pore water as well as the mineralogy and the porosity. Variations in these parameters are probably causing the poor moisture content correlation. Removal of 14 high moisture values out of a total of 227 observations increases the R value for the Neutron Porosity versus moisture content from 0.23 to 0.52. Further study of this data could improve the R value.

4.5.2 Undrained Shear Strength

The undrained shear strength (Q_u) has been plotted against the gamma log on the theory that strength is inversely related to clay content. The correlation plots show a weak reverse relationship. A somewhat stronger correlation between Q_u and the Density log is demonstrated. Here correlation coefficients of 0.54 and 0.72 have been obtained. The latter value was achieved for a semi-logarithmic plot. However, this correlation plot suffers from a small data population.

It is well known that undrained shear strength is a function of stress history for sediments which are overconsolidated such as the Clearwater Formation. Consequently, correlation of Q_u with index properties are generally not very strong.

4.5.3 Liquid Limit (Atterberg Limit Parameter)

This parameter is an empirical test which arbitrarily measures the moisture content of clay rich soils at which a soil passes from a plastic state to a liquid state. The property is sensitive to the percentage of clay present as well as the clay mineralogy. In correlation attempts with the gamma log, both linear and semi-logarithmic plots show no correlation. The R values are 0.03 and 0.05 respectively. In addition, there is considerable data scatter. A very poor relationship is also obtained with the density log with an inverse relationship shown on the plot.

4.5.4 Plasticity Index (Atterberg Limit Parameter)

This property is defined as the difference in the liquid limit and the plastic limit. This property indicates the moisture content range over which a soil remains plastic.

Because of the amount of data available, plasticity values were correlated separately for each shale member of the Clearwater Formation against the Gamma Log. The following summary highlights the results.

<u>Member</u>	<u>Linear Plot</u>	<u>Semi-Logarithmic Plot</u>
Kcw	0.71	0.71
Kca	0.33	0.27
Kcb	0.13	0.11
Kcc	0.45	0.49

In all cases the R values are positive, but only the Kcw member provides a promising correlation coefficient. This result may have some ramification on all other correlation plots since it shows that successful correlation may be dependent upon the stratigraphic member. When plotted against the Density Porosity Log, the plasticity was shown to decrease as density increased. However, considerable scatter in the data renders weak correlation coefficients of -0.43 and -0.44 for the semi-logarithmic and linear plots, respectively.

4.5.5 Grains Size Correlations

Synchrude was able to provide a large quantity of particle size analysis data. While these parameters were originally defined as having a low priority by the Correlations Group, the availability of the data were seen as an opportunity to develop several correlations.

- Fines Content. The fines content (less than 0.002 mm per cent by weight) when plotted against the Resistivity, Neutron-Porosity, Density-Porosity and Gamma Logs produced generally poor correlations with a large scatter in the data plots. The highest R coefficient at 0.54 was obtained with the Gamma Log on a semi-logarithmic plot. However, all of the plots contain a large amount of scatter.
- Silt Content. The silt content is defined as the size range between 0.002 mm and 0.06 mm. The plots of this parameter against Resistivity, Neutron-Porosity, Density-Porosity and Gamma Logs are extremely poor and show no promise.

- Sand Content. The sand content is defined as the Size Range between 0.06 and 2.0 mm. Correlations were completed for the same geophysical logs as for the silt and fines fractions. A reasonable correlation ($R = 0.72$) was achieved for both linear and semi-logarithmic plots against the Gamma Log. As expected the Gamma Log value increases as the sand content decreases. While this plot produces a reasonable correlation coefficient the scatter of the data is still large and individual estimates of sand content inferred from a Gamma Log value could be in considerable error.
- Grain Size Uniformity. The slopes of the grain size curves, as a quantitative value representing the uniformity of material, were calculated and then plotted against the four major geophysical logs with Gamma Log providing correlation coefficients of -0.62 and $+0.62$ values for the linear and semi-logarithmic plots. The semi-logarithmic plot shows a relatively small amount of data scatter. The curve appears to offer promise for further refinement with additional data.

4.5.6 General

The approach followed in the correlations discussed above was to use all of the data provided by Syncrude. Attempts were made to establish trends between geotechnical parameters and the various geophysical logging tools. Some trends were established between Q_u and Density Log, moisture content and Neutron Porosity, K_{cw} and Density, fines content and Gamma Log and between sand content and the Gamma Log. All of these correlations showed a wide scatter of data and low R values. Additional studies are required to cull data with the purpose of improving the correlations.

5. HYDROGEOLOGICAL - COAL FORMATIONS

5.1 Data Search

Alberta Research Council (ARC) conducted the evaluation of hydrogeologic and geophysical log data. The initial task assigned to ARC was to determine the relationship between hydrogeological parameters and geophysical log data using existing data. This task was expanded during the study to include analysis of a similar data set supplied by TransAlta Utilities Corporation (TransAlta).

The ARC data were selected from a recently completed program which studied the effects of open cast mining and reclamation on the groundwater environment in the Highvale Coal Mine and the Battle River Coal Mining regions. See Figure 2 in Section 2.3. Groundwater data was also selected from ARC's Highwall Stability study at Highvale Mine in 1983. Additional data were provided by TransAlta from investigations at the Highvale Mine, 1983 to 1986. Geophysical logs and in most cases lithologs were available for the boreholes.

Data from the Highvale Mine came from Upper Cretaceous to Lower Tertiary age sediments of the Ardley coal zone that belong to the Lower Paskapoo Formation. The coal resources of the Battle River Mining area come from Upper Cretaceous Age sediments of the Lower Horseshoe Canyon Formation. See Figure 4 in Section 2.3.

5.1.1 Hydrogeologic Parameters and Data

The ARC review of the records revealed the following data:

<u>Parameter</u>	<u>Number of Measurements</u>
Hydraulic conductivity (K)	84
Water table (saturation)	33
Fluid conductivity (chemistry, salinity, T.D.S.)	300
Pore pressure	135

Initially, correlations were to be carried out on each of these parameters. However, retrieval and organizing of all the required data into a usable form proved to be a more difficult and time consuming task than anticipated. Therefore, the evaluation and correlations attempted in this study focussed on one parameter which was judged to be the most important from the available data, the hydraulic conductivity (K). A total of 45 hydraulic conductivity values were selected in the correlations and are shown in Table 8.

The hydrogeologic data were collected from open piezometer stand pipes. Typical piezometer well completion consists of one screened interval within a sand or gravel pack per hole. A pelleted bentonite seal is placed above and below the sand pack. See Figure 9.

5.1.2 Geophysical Log Data

Suites of geophysical logs were available for the boreholes from which the hydraulic conductivity data were obtained. The number of logs used for each of the 3 data sets is summarized in Table 9. All the holes were geophysically logged by BPB Instruments (Canada) Ltd. between 1979 and 1986. Specifications of BPB geophysical tools are provided in Appendix II.

Table 9

GEOPHYSICAL LOGS USED FOR HYDROGEOLOGIC CORRELATIONS

<u>DATA SET</u>	<u>GEOPHYSICAL LOGS</u>							
	<u>Gamma</u>	<u>Density</u>	<u>Caliper</u>	<u>Neutron</u>	<u>Focused Electric</u>	<u>Long Sonic</u>	<u>SP</u>	<u>Resistivity</u>
ARC-Battle River (1979-1982)	3	3	3	3	-	-	3	3
ARC-HV Mine (1983)	8	8	8	2	7	5	-	-
TAU-HV Mine (1983-1986)	15	15	15	6	14	11	-	-
Total	26	26	26	11	21	16	3	3

NOTE: Density log is long spaced density in units SDU (BPB Standard Units).
Neutron log is dual spaced neutron in units SNU (BPB Standard Units).

The data from geophysical logs that were used in our analysis originated in hard copy form. Logs from selected boreholes were digitized using Logmate, ARC's log analysis computer system to provide numeric values for each log curve at 10 cm depth intervals.

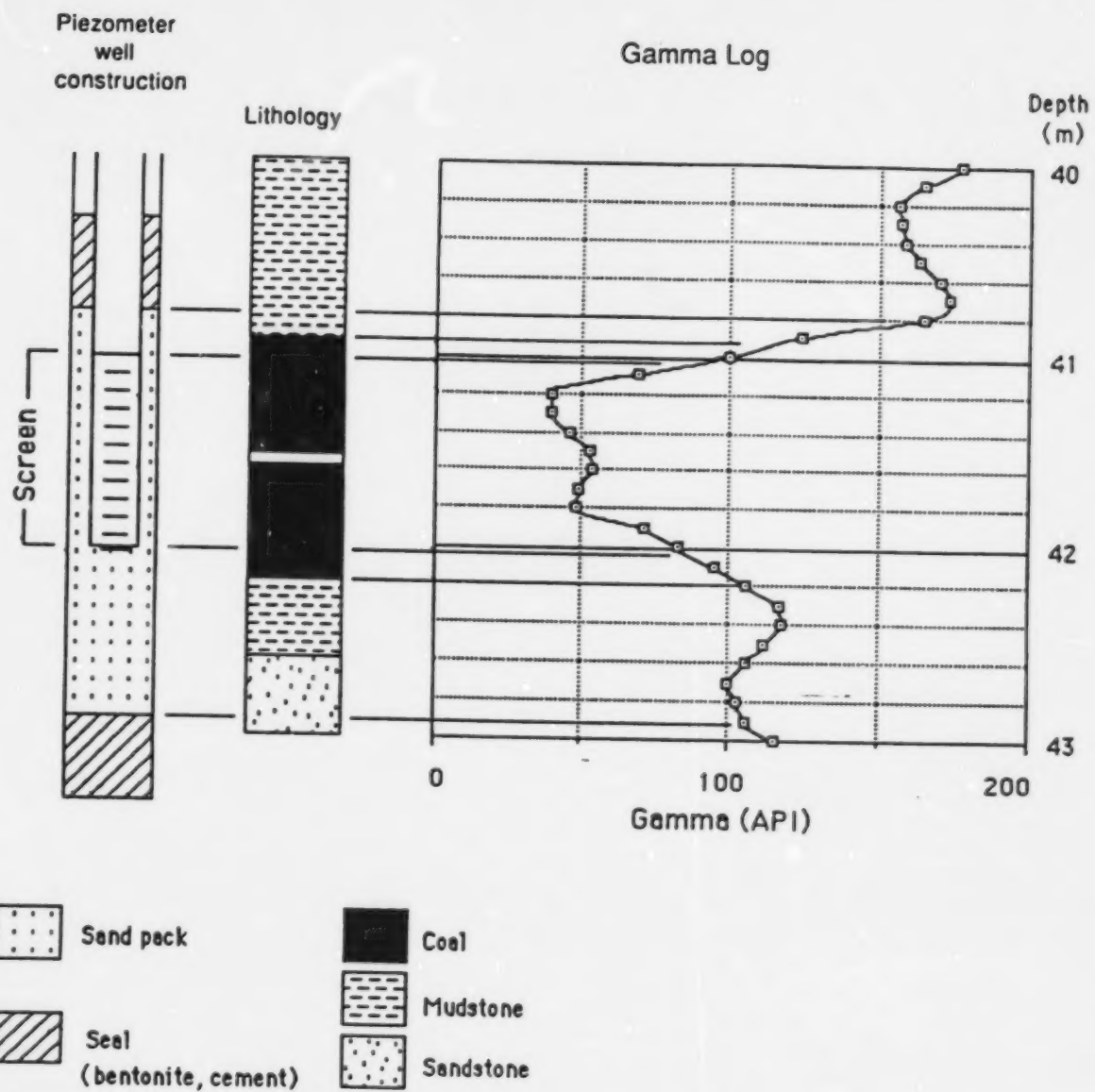


Figure 9. Relationship of piezometer well construction to stratigraphy and a geophysical log.

5.2 Methodology

The approach to the analysis of the data was to first make simple comparisons on a microcomputer of geophysical log values. The objective of this first comparison was to determine whether or not trends were evident and whether simple conclusions could be made.

Additional statistical computations were then carried out on the mainframe computer. The objective for this phase was to see if any trends could be recognized from the correlations. If so, these could be further investigated in the next phase of the project. Details of the data analysis procedures are presented in Appendix V.

For this study, the piezometer screen interval was chosen as the zone thickness of interest for correlation. The field of data was further narrowed down specifically to analyze measurements in coal. Several factors made it difficult to choose the correct geophysical log values that would be representative of the screened zone. These are discussed below in Section 5.2.1.

In order to maintain a degree of uniformity in choosing the geophysical log values, it was decided that all the geophysical log values that fell within the depth interval of the piezometer screen would be used to come up with an average value that would represent the zone (Figure 9). This method includes log values representing adjacent beds. No editing or filtering of the geophysical log data was used to account for noncoal values (i.e. parting, roof or floor rock). Future correlations should be undertaken using different criteria for selection of geophysical log values for the screened interval in coal.

5.2.1 Problems Encountered

Several obstacles and problems became apparent during data analysis. Some of these could not be easily resolved and may have a direct affect on the correlation results. These should be addressed in the next phase of the project work plan prior to collection of new data. Major problems identified are:

- 1) Access to Data. It became apparent very early in the data analysis that retrieving and compiling the necessary data would not be an easy task. The hydrogeologic data at ARC were in a computer data base, however, there was no direct link between the data files and the computer analysis programs. The data that were used in this study had to be entered manually. The ARC geophysical log data were even more difficult to access electronically. Data were available on cassette tapes in their field format. To get

the data into usable form for the analysis programs would have required several reformatting steps. This proved to be too costly. The alternative was to hand digitize a much smaller data set.

- 2) Proper Well Completion. Three choices were available in selecting the correct depth interval of the zone to be tested hydrogeologically. Should the screen interval, sand pack interval, or lithologic interval be used to represent the interval of the hydrogeologic zone? Figure 9 illustrates how each interval gives different ranges of gamma values for a coal seam that was targeted for testing. Ideally, the piezometer well should be completed so that screen and sand pack cover the exact depth interval of the seam. In practice, this is rarely the case and unrealistic to expect. In order to simplify our analysis, the screened interval was selected to represent the zone of interest from the geophysical log data.
- 3) Geophysical Log Curve Values. One of the biggest drawbacks with data from the geophysical logs is insufficient resolution. This factor poses a problem in determining which interval of geophysical log values should be used to calculate the average for the zone of interest.

The log curve values do not accurately represent the total thickness of a lithologic unit. Ideally, lithologic contacts would produce instantaneous changes in geophysical log responses. The inability of geophysical equipment to produce these instantaneous changes is due to the physical limitation of the downhole tool. Some logging tools have a better resolution than others. The Focussed Electric or Microresistivity Log has a resolution of about 10 cm compared to the Gamma Log which is in the order of 60 cm. However, with advanced recording equipment able to take a digital reading every centimetre, this means a minimum of 10 nonrepresentative values. Even though one tool has better resolution than the other, the problem remains about what to do with those values within the transition zone on the log that correspond to lithologic contacts. Depending on the volume of the data, these could be eliminated.

As an example (Figure 9), taking a coal seam that is 1.3 m thick with a gamma reading of about 50 API, what values from the log curve should be used to represent the true thickness of that seam? Several choices are available:

- . Use all of the absolute geophysical log values over that 1.3 m interval.

- . Block the log curve to give a value of 50 API over the entire 1.3 m interval.
- . Use pure coal values only, i.e. filter out the partings values, and transition values at the contact with roof and floor rock.

Choosing the proper values to calculate the representative average of a zone can become a matter of interpretation. For this study, the actual geophysical log values were chosen, without any manipulation or filtering except for averaging, to represent the screened depth interval for correlations. Further analysis is required for a comparison of correlation results using the different criteria for geophysical log value selection to see which method is correct.

- 4) Calibration and Corrected Log Values. Calibration or corrections to log values to account for different variables needs to be studied. This does not necessarily apply to the actual calibration of the geophysical equipment itself. Other factors that may have an effect on correlation are: drilling fluid resistivity, drilling fluid density, hole diameter, and mineralogy.

The physical, chemical and electrical properties of the drilling fluid could have adverse effects on any quantitative analysis of the data. The effects of fluid conductivity is shown in an example of a corrected vs uncorrected log curve for the Focussed Electric log in Figure 10. This information should be requested from the logger and properly recorded in the field so that corrections can be incorporated into the log plot for subsequent data analysis.

5.3 Correlations

5.3.1 Simple Linear Regression Analysis

The first attempt at correlations for coal between hydraulic conductivity (K) and geophysical logs was carried out on a Macintosh microcomputer. Scatter plots were made of each geophysical parameter against the log of the hydraulic conductivity. The data used for the correlations were taken from Table 8. Two separate plots were made for each geophysical log, one using only values for coal and the other using values for both coal and noncoal material. The noncoal data included values for sandstone, siltstone, mudstone, till, sand and

gravel. The graphs are presented in Appendix V. A simple regression fit has been applied to the data in the graphs which shows the equation and the 'best fit' line through the data points. The results are summarized in Table 10.

Initial observations in this study suggest that there is a low correlation between hydraulic conductivity and the geophysical logs. Trends may not have been detected because of the small number of data points used for many of the plots. Statistically, additional data are required to confirm the results.

There appears to be a lithologic influence to the plots. A comparison of the coal to noncoal graphs for several correlations show that two fields of data points are present. This is illustrated in the plots of the log of hydraulic conductivity against density for both coal, and coal and noncoal values (Figure 11). This suggests that all the data should not be grouped together for correlation because the rules for one lithology may not necessarily apply to the other. Each field of data should be interpreted separately. Additional correlations should be run with sandstone and mudstone data sets to see if they occupy separate fields within the scatter plots.

Observations of the graphs show that for coal, the neutron porosity plots appear to have the best correlation with hydraulic conductivity (Figure 12). The graphs show that as the neutron counts increase, hydraulic conductivity decreases ($R = 0.79$ and 0.74 for ARC and TransAlta respectively).

Table 10 Summary of hydrogeologic correlations attempted in first pass of analysis.

<u>Correlation</u>	<u>Equation</u>	<u>R Value</u>	<u>n</u>
Log K vs Gamma (coal)	$\text{Log K} = -4.5188 - 0.036 \text{ Gamma}$	.39	30
Log K vs Gamma (coal & noncoal)	$\text{Log K} = -6.9778 + 0.013 \text{ Gamma}$	.69	44
Log k vs Log FE (coal)	$\text{Log K} = -12.8662 + 2.9047 \text{ Log FE}$	.48	20
Log K vs Log FE (coal & noncoal)	$\text{Log K} = -6.2077 + 0.5077 \text{ Log FE}$	.20	31
Log K vs Density (coal)	$\text{Log K} = 15.7357 - 15.3532 \text{ Density}$	.52	28
Log K vs Density (coal & noncoal)	$\text{Log K} = -2.2085 - 1.6915 \text{ Density}$	.36	42
Log K vs Sonic (coal)	$\text{Log K} = 27.329 - 0.2576 \text{ Sonic}$	.50	13
Log K vs Sonic (coal & noncoal)	$\text{Log K} = -4.3298 - 0.0083 \text{ Sonic}$	.22	19
Log K vs NN (ARC coal)	$\text{Log K} = -2.3264 - 0.0894 \text{ NN}$	.79	12
Log K vs NN (ARC coal & noncoal)	$\text{Log K} = -4.199 - 0.0139 \text{ NN}$	.63	16
Log K vs NN (TAU coal)	$\text{Log K} = 42.2788 - 0.0314 \text{ NN}$	.74	8

Where: Log K = log of hydraulic conductivity
 Log FE = log of Focussed Resistivity
 NN = Dual Spaced Neutron (Porosity)
 R = correlation coefficient
 n = number of samples
 Density is bulk density measured in grams/cc

Correlation graphs are presented in Appendix 10.4

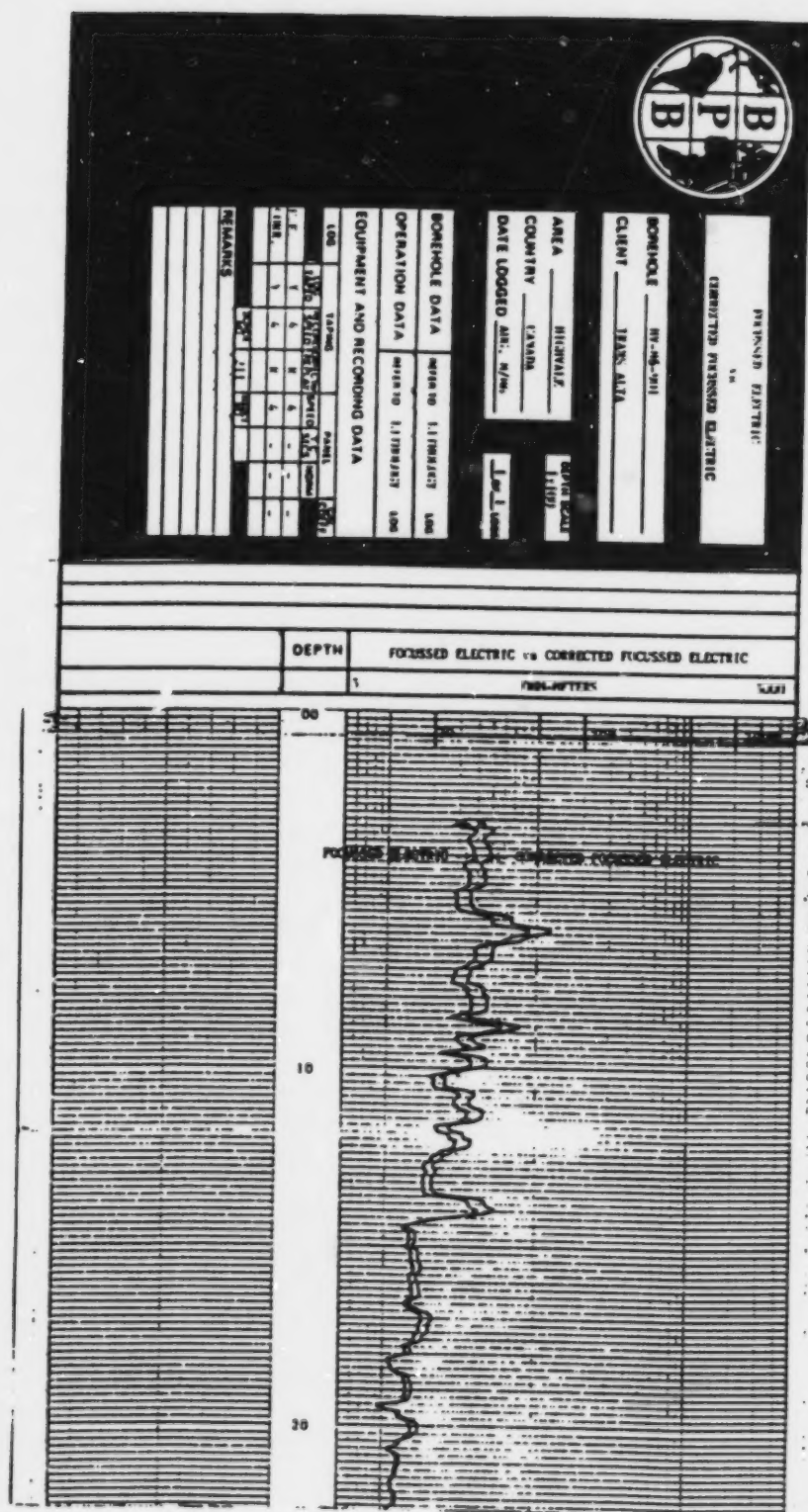


Figure 10: Example of borehole fluid correction for focussed electric log.

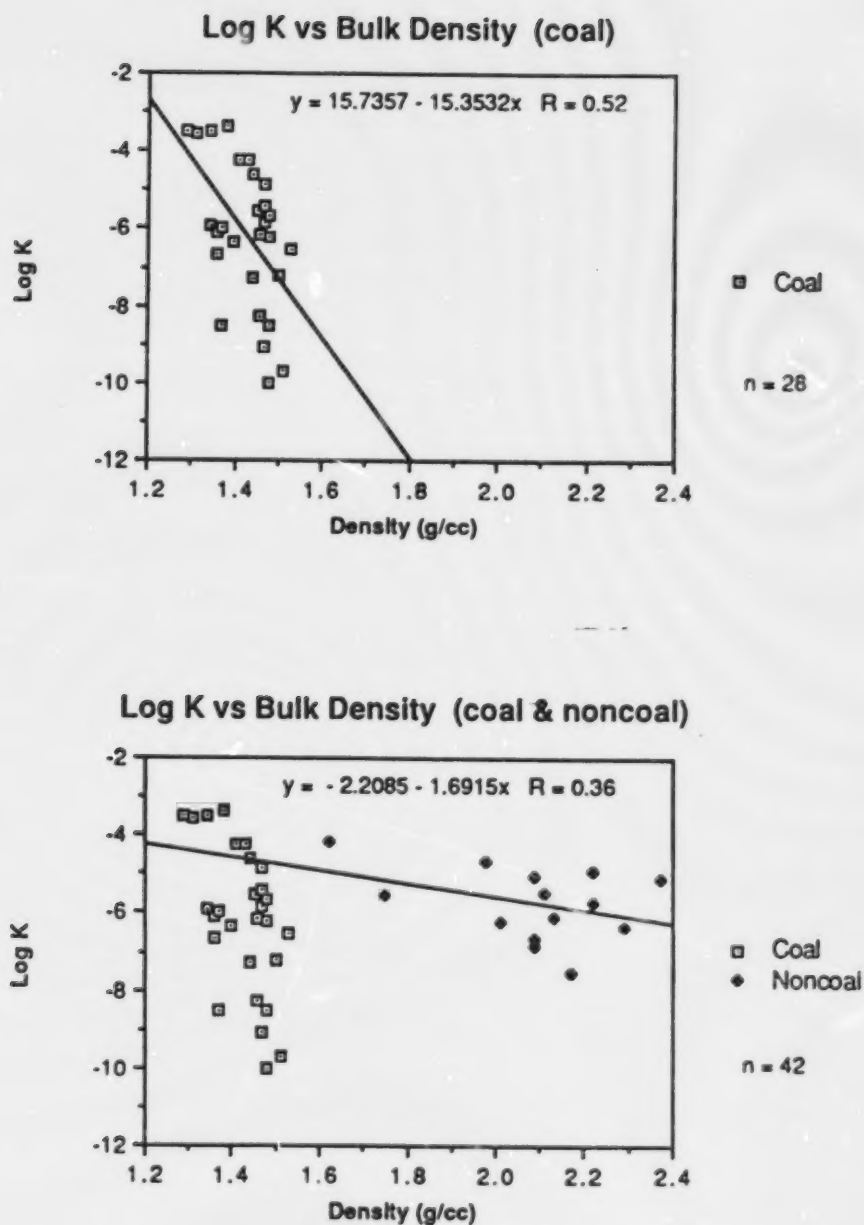


Figure 11 Scatter plot, Log K vs Bulk Density.

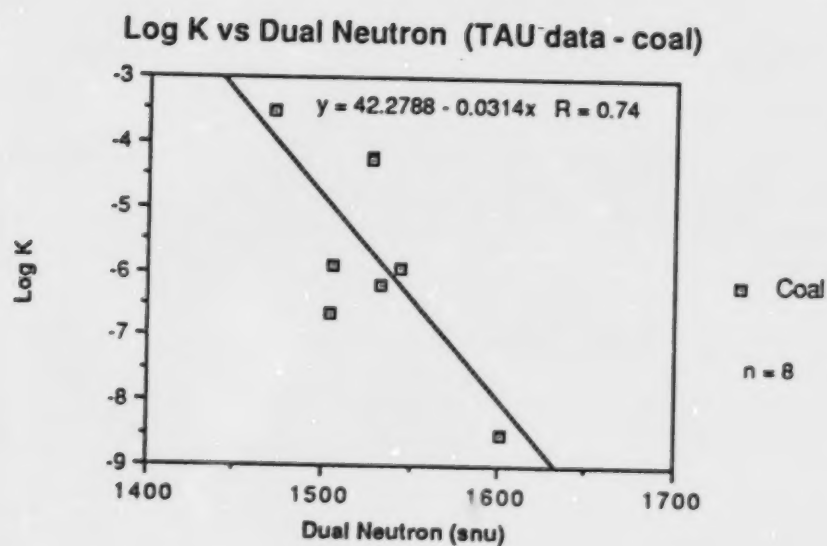
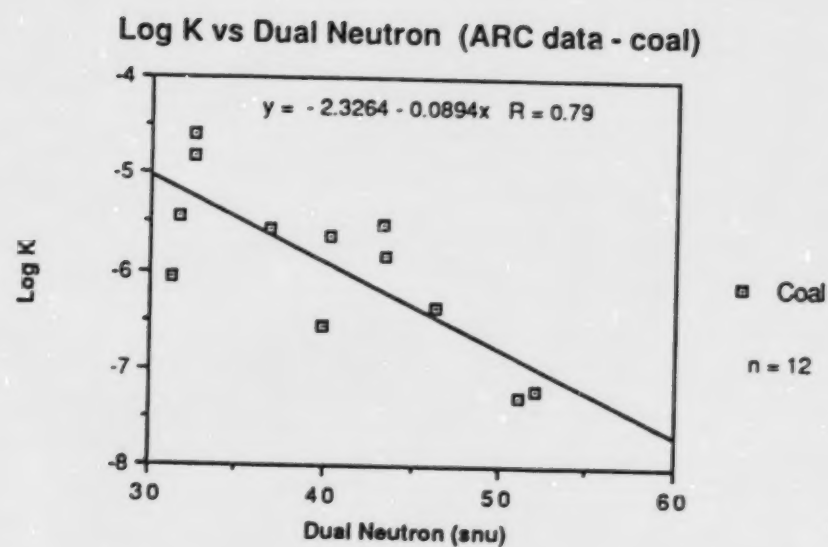


Figure 12 Scatter plot, Log K vs Dual Spaced Neutron

5.3.2 Multiple Regression Analyses

A second stage of correlations was performed on the mainframe computer with a more sophisticated statistical program. This program allowed for a more rigorous analyses. These included significance tests of the relationships and of the parameters describing the relationships. The following discussion contains several references to statistical measures of significance. These measures are based on statistical theories beyond the scope of this report. Small probability values are indicative of greater significance. The adjusted R^2 is an estimate of the correlation between measured values and values estimated by the regression equation.

The first step in studying the relationship between geophysical logs and hydraulic conductivity values for coal was to conduct simple linear regression (SLR) analysis of each geophysical parameter against the log of the hydraulic conductivity (Table 11). Three geophysical parameters displayed relationships with hydraulic conductivity that are significant at the 5% level or better, (1) both the original values and logarithm of the focused electric log, (2) density (sdu) and, (3) natural gamma (Table 12). Even the best model, the log focused electric log, has an adjusted R^2 value of only 0.3413. Thus, it is evident that most of the variation in hydraulic conductivity is unrelated to variation in the geophysical logs. From these SLR analyses, the neutron log and calculated bulk density values have a limited relationship to log hydraulic conductivity. F-values are significant at the 8.78% and 6.79% levels respectively (Table 11). The sonic log displays essentially no relationship with the log hydraulic conductivity (Table 11).

Multiple regression models were evaluated to determine whether any combination of geophysical logs might be more strongly related to the log of hydraulic conductivity than were the individual logs. Four 2-parameter and four 3-parameter models were calculated.

The highest values of adjusted R^2 were found with three models that combined the logarithm of the focused electric log successively with standard density units, bulk density, and natural gamma (Table 12). The best of these models, the standard density units combined with log of focused electric, showed slightly more than half the variability of the hydraulic conductivity. This was also the only model that had at least one of the coefficients better than the 5% level.

The two parameter model involving gamma and density was the only model that could utilize all 28 of the samples in the data set (Table 12). This model had an adjusted R^2 of only 0.212, and an F-value of 4.631, which is significant at the 1.95% level. The t-value of the coefficient for the gamma ray log value is -2.251, which is significantly different from zero at the 0.0334 level. However, the coefficient for the density value is significantly different from zero only at the 0.8257 level.

TABLE 11 SUMMARY OF LINEAR REGRESSION MODELS RELATING LOG
HYDRAULIC CONDUCTIVITY TO GEOPHYSICAL LOG PARAMETERS.

		LOG FE	ADJRSQ	EVALUE	PROB>E	N
LOGK =	-15.1714 + 4.138981 T = 3.048 PROB. OF T = 0.0081		0.3413	9.291	0.0081	17
LOGK =	-3.72369 - 0.0491047 GAMMA -3.092 0.0047		0.2408	9.562	0.0047	28
LOGK =	-8.36273 + 0.0105303 FE 2.453 0.0269		0.2387	6.017	0.0269	17
LOGK =	-10.1116 + 0.000903 DENSITY (SDU) 2.857 0.0083		0.2097	8.164	0.0083	28
LOGK =	-5.92288 + 0.0005842 NEUTRON 1.818 0.0878		0.1194	3.306	0.0878	18
LOGK =	2.365785 - 5.78622 BULK DENSITY -1.905 0.0679		0.0887	3.628	0.0679	28
LOGK =	-14.2764 + 0.0540413 SONIC TRANSIT TIME 0.922 0.3783		-0.0138	0.85	0.3783	12
LOGK =	0.526409 - 0.0033076 SONIC VELOCITY -0.75 0.4705		-0.0414	0.563	0.4705	12

TABLE 12 SUMMARY OF MULTIPLE REGRESSION MODELS RELATING LOG HYDRAULIC CONDUCTIVITY TO GEOPHYSICAL LOG PARAMETERS.

Two Parameter Models

LOGK =		FE	+	0.002	DENSITY (SDU)	ADJRSQ	EVALUE	PROB>F	N
	-16.44	0.8732		2.564		0.5198	9.66	0.0023	17
	PROB. OF T =	0.62		0.023					
LOGK =	13.523	DENSITY	+	1.4652	LOG FE	0.4399	7.282	0.0068	17
	-1.908			0.78					
	0.0772			0.4486					
LOGK =	-15.33	GAMMA	+	4.1933	LOG FE	0.2943	4.336	0.0342	17
	0.027			1.724					
	0.9786			0.1068					
LOGK =	-4.873	DENSITY	-	0.0529	GAMMA	0.212	4.631	0.0195	28
	0.223			-2.251					
	0.8257			0.0334					

Three Parameter Models

LOGK =		DENSITY	+	0.011	GAMMA	-	0.0784	NEUTRON			
	-2.345	0.1226		-0.56			-2.51	0.5201	4.974	0.031	12
	PROB. OF T =	0.9522		0.597			0.0364				
LOGK =	18.288	DENSITY	+	0.0488	GAMMA	+	3.0088	LOG FE	5.702	0.0102	17
	-2.364			1.325			1.387				
	0.0343			0.208			0.1889				
LOGK =	50.58	DENSITY	+	0.0453	GAMMA	-	0.0326	TRANSIT TIME	3.96	0.0531	12
	-2.596			0.994			-0.638				
	0.0318			0.3495			0.5413				
LOGK =	26.791	DENSITY	+	0.0355	GAMMA	+	0.005	FE	4.958	0.0165	17
	-2.479			0.989			0.904				
	0.0277			0.3406			0.3826				

Four different three-parameter models were evaluated (Table 12). In these models the gamma and density values were combined successively with the sonic, focused electric, log of the focused electric and neutron logs. These models had adjusted R^2 values that range from 0.5201 for the neutron log ($n=12$) to 0.426 for the focused electric ($n=17$). In each model the coefficient of only one parameter is significantly different from zero (Table 12). For the models that included sonic transit time, log focused electric, and focused electric logs, only the density is significant, with t-values of -2.596 (significant at the 3.18% level with $n=12$), -2.364 (significant at the 3.43% level with $n=17$), and -2.479 (significant at the 2.77% level with $n=17$), respectively. In the fourth model, only the coefficient for the neutron log is significant with a t-value of -2.51 (significant at the 3.64% level with $n=12$).

5.4 Discussion

On the basis of the preliminary regression analyses that have been carried out, there is little indication that the hydraulic conductivity of coal can be effectively estimated on the basis of geophysical log parameters. As is indicated by the low values of R^2 for all the models evaluated, most of the variability in hydraulic conductivity is not related to any individual log or any combination of logs included in this study.

The slight trends that exist are consistent with the theoretical relationships. Further work is required to refine the selection of hydraulic conductivity and the geophysical log values used in this analysis before it can be concluded that geophysics cannot be used to estimate hydraulic conductivity. Additional data sets should be obtained to confirm that this indication is not masked by insufficient data.

6. NEW GEOPHYSICAL PROBES

6.1 Selection of New Tools Based on Results of the Phase 2 Study

The results of the geotechnical correlation studies show that the gamma, sonic and gamma-gamma (density) geophysical probes have provided the most promising correlations. In the light of this information, it is suggested that enhancements to these tools and/or methods should be given careful consideration for the Phase 3 portion of the program. In keeping with the findings of the Phase 1 study on new tools, testing of a more sensitive gamma tool, a gamma spectral tool and a full waveform seismic tool are discussed in this chapter and recommended for consideration in Phase 3.

6.2 High Sensitivity Slim Line Gamma Probe

The gamma tool detects natural gamma radiation emanating from common radioactive isotopes including those of Potassium (K40), Thorium (Th232) and Uranium (U238). A high sensitivity tool (Geosource model T31 Gamma Ray Probe) has been developed especially for coal survey work to evaluate interseam and interply layers. It has a tool diameter of 4.2 cm and is easily integrated with logging systems of most other manufacturers. The tool can accommodate a variety of logging speeds. Because of its higher sensitivity, data derived from this tool may provide better correlations than the standard gamma tools.

6.3 Spectral Gamma Ray Probe

While this tool is not "new", it has not been used in coal and oil sands operations in the Western Plains. The probe's primary function is to resolve the relative amounts of Uranium, Thorium and Potassium radioactive isotopes. Removal of the uranium component from the total gamma ray curve allows a better estimate of the total clay volume. Similarly, specific ratios of Th/K, U/K and U/Th allows the determination of clay types (kaolinite, bentonite, illite, chlorite). These clay data can then be correlated with geotechnical data such as Atterberg Limit parameters and perhaps strength parameters.

6.4 Full Wave Form Sonic Probe

As shown in the correlation section of this report the P-wave sonic log has provided a good correlation with uniaxial compressive strength (Q_u). With further refinement of the sonic technique it may be possible to provide improved correlation coefficients over those

already obtained; the calculation of dynamic elastic moduli; and correlation with other geotechnical parameters such as effective shear strength, and tensile strength.

A compensated sonic sonde capable of providing a full wave form output together with time increments up and down in the borehole wall and a compensated time increment is available from BPB and other companies. Given the full wave form on a detailed (i.e. 10 cm) increment basis, it should be possible to identify the first shear wave arrival and transit time for this arrival. The shear wave data will provide elastic moduli and may be used as a correlative with the aforementioned geotechnical properties. In addition, tube wave amplitude related to hydraulic conductivity has been reported elsewhere.

6.5 Other Oil Field Tools with Potential Application

The Phase 1 report (Chapter 2) raised and revived a variety of downhole geophysical probes which have not been normally employed in coal field and oil sand evaluation programs. A total of fifteen possible methods were briefly reviewed in terms of their potential application to slim hole logging programs which are normally carried out for coal and oil sand reserve estimates.

A number of these tools are only available in large diameter configurations including:

- a) Formation Microscanner
- b) Measurement While Drilling (MWD)

These tools are expensive systems to operate, require large diameter holes and do not provide information that is unique and relevant to these studies. Consequently, test trials with this equipment are not recommended.

An Acoustic Televier is also available for logging 3 inch holes and may be of use in investigating the contribution of fractures to hydraulic conductivity.

6.6 Other New Slim Hole Tools

New slim hole tools which were included in the Phase 1 report (Chapter 7) are discussed very briefly:

Impluse Radar Methods. While very encouraging results have been obtained in hard rock environments, a review of detailed technical reports supplied by the Geological Swedish Company shows that water saturated materials with resistivities of 10 ohm metres or less allow

very little penetration of the radar signal. Since most of the overburden lithologies of the coal and oil sand areas have relatively high conductivities it is highly unlikely that this method would not provide satisfactory results.

It should also be noted that surface radar systems, as opposed to borehole systems, have been tested in the oil sands. Poor penetration results were achieved.

Radio Imaging Method (RIM). This is an electromagnetic system based on a transmitter-receiver configuration from borehole to borehole. This method performs satisfactorily in coal fields with an electrical conductivity range of 5×10^{-4} to 5×10^{-1} mhos/m for coal and associated lithologies. However, the RIM methods have been developed to determine structural geology features such as faults, pinchouts, washouts and interseam splits. It has not been developed for specific geotechnical application. However, since these structural geology features often play a role in geotechnical mine design the method should be seriously considered for test trials in Phase 3 of this program.

An application of the method is foreseen in hydrogeology of oil sand leases. Delineation of the basal aquifer may be possible because of the conductivity contrasts between the overlying oil sand and the underlying limestone. Mean conductivities for these layers are estimated at 10^{-3} , 5×10^{-2} and 5×10^{-3} mhos/m for the oil sand, basal aquifer and limestone, respectively. This service is available from Stolar Inc. and the Southwest Research Institute.

Heat Pulse/Thermal Logging. The Geological Survey of Canada has offered the use of their thermal probe for measuring temperature gradients and computing lateral groundwater flows could be made available if sufficient notice is provided. Since the system is available free of charge and given the appropriate conditions (i.e. an area where low groundwater flow rates are expected as a result of mine dewatering or some other activity), it appears that this method should be tested.

Jessop (1987) has developed a method for estimating lateral flow by injection and thermal logging. This method is simple in principle but requires sophisticated mathematical modelling techniques to interpret the thermal data.

Low Frequency Pulse EM Probe. This system has been developed to locate and delineate sulphide ore deposits. It is designed to locate "off-hole" conductive zones in the presence of "in-hole" sulphides. The method operates with a horizontal transmitter loop at surface and a receiver probe in one or more boreholes which may be located inside or outside the transmitter loop. While the method functions well for host rocks with apparent resistivities in the range

of 10 to 100 ohm metres, it is not certain that potential targets such as the basal aquifers in the oil sands would have sufficient resistivity contrast to provide "off-hole" geometries. Trial of the method in coal and oil sands should await test results in less resistive sedimentary host rock environments.

6.7 Prioritization of New Probe Tests

The costs involved in testing new borehole geophysical probes, especially oil field tools, is high. In addition, geotechnical data and/or hydrogeological data must also be obtained for each hole tested. This requirement adds to the cost.

Given the results of the geotechnical correlations and the preliminary values for the hydrogeology correlations it is suggested that further study be first focussed on certain standard logging tools including the gamma probe, the neutron sonde, the sonic tool and the gamma-gamma or density tool. Should additional funds be available, a second group of new tools which should be seriously considered are the Radio Imaging Method and Thermal Logging Tools for measuring lateral groundwater flow.

The gamma tool has two variants which are recommended including the high sensitivity tool from Geosource and the spectral gamma ray probe which is available from several oil field contractors. The former probe may provide correlation better than those already obtained because of its sensitivity. The latter probe provides individual response curves for the three common naturally occurring radioactive isotopes, (K, Th and U). Consequently, correlation with certain properties such as Atterberg Limits or undrained shear strengths may be improved. Clay mineral species groups may also be determined by the spectral tool.

The other probe recommended for further test work is the full waveform sonic tool. It will provide data for elastic moduli computations as well as shear wave data for correlation with various strength values. Preliminary analysis of TransAlta's sonic data shows sufficiently good correlations with P-wave data and unconfined compressive strength that this method should be pursued. An alternative sonic probe (5 cm diameter) is available from the Southwest Research Institute in San Antonio, Texas. However, this system was especially developed for the U.S.G.S. and may require extended lead time to arrange for delivery to Canada. This P-wave and S-wave system has a receiver separation distance of 1 metre which may need to be changed so as not to limit the resolution of the tool.

Further efforts at correlating density log data with bulk density data should be focussed on obtaining standardized calibration of contractor's density tools at a single site (i.e. ISPG, Calgary) and

collection of reliable density data. Application of the method to reworked materials (i.e. spoil and tailings) may also offer other opportunities for the density tool. New density tools with improved bed resolution would also be quite useful.

The last group of new tools which are recommended for consideration includes the hole to hole electromagnetic system. This system is designed to operate between pairs of vertical boreholes using pulsed radio frequency signals. The method was developed primarily to probe the continuity of lithologic materials between boreholes. As such it could have application in the coal fields for determining pinchouts, faults, etc. In the oil sand area of Fort McMurray, average conductivity data for oil sand, the basal aquifer and the underlying Devonian Limestone suggest that the method could be used to delineate the continuity and extent of the basal aquifer. The method is supported by at least two commercial sources; the Southwest Research Institute in San Antonio and Stolar Inc. of Albuquerque, New Mexico.

Thermal logging tools appear to have special applications in measuring lateral and vertical groundwater flows, especially where flow rates are below the threshold levels of the mechanical or impeller tool types. Trial applications of this method are warranted if the Geological Survey of Canada can make its equipment available. Also A.E. Hess of the USGS has developed a high sensitivity thermal flow meter to measure vertical flow in stem holes.

In summary, those Geophysical Probes which appear to have merit in either refinement of their application or new application testing are; high sensitivity gamma, spectral gamma, neutron, gamma-gamma (density), S-wave and P-wave sonic or full wave form sonic, hole to hole electromagnetic, thermal and acoustic televiewer.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Geotechnical - Coal Formations

Based on the Highvale data studies, a number of correlations between geotechnical and geophysical parameters have been established with correlation coefficients greater than 0.8 (see Table 3).

The geophysical logs which give the best correlations are the Neutron, Density and Sonic Logs. Although more work is required to confirm the universality of some of these relationships, credibility for the uniaxial compressive strength vs sonic transit time relationship is strengthened by the good agreement with similar data from Australian Mines (see Figure 6).

For those relationships which exhibit correlation coefficients less than 0.8, enhancement of the correlation may be possible by increasing the number of observations, by pairing combinations of parameters, by considering individual lithologic units separately or by more rigorous scrutiny of the data to ensure consistency.

It is recommended that additional studies be carried out to confirm the correlations obtained and ascertain if additional relationships between geotechnical and geophysical parameters can be established. To this end, the following procedures should be considered:

- . The minimum number of observations required to ensure a given relationship is statistically significant should be determined by appropriate analyses.
- . The minimum value of the coefficient of correlation to adequately define a reliable correlation should be established.
- . Additional geophysical data collected by Century Geophysical and available with TransAlta should be reformatted and included with the corresponding geotechnical data in future correlations.
- . Data from different sites should also be included in future correlations. This includes data from Whitewood Mine, Syncrude Mine and available published data.
- . Individual lithologic units should be evaluated separately. These should also be grouped according to depth to ascertain degree of glacio-tectonic disturbance.
- . Combinations of parameters should be paired to obtain upgraded correlations if necessary.

- Only log data corresponding to the lithologic unit represented by the core or test should be selected.
- Non linear regression analysis should be attempted on this data.
- The variation in tool calibration and tool types from year to year and the effects on correlations should be evaluated.
- Attempts should be made to correlate geophysical logs with other geotechnical parameters such as effective shear strength and consolidation properties of mine spoil.

7.2 Geotechnical Oil Sands Formations

The paired parameters listed in Table 7, with R values greater than 0.7 suggest that correlations can be established between the following:

	R Coefficients	
	Linear	Semi-Logarithmic
Moisture Content vs Bulk Density	-0.77	-0.76
Undrained Shear Strength vs Gamma	--	0.72
Plasticity Index vs Gamma Log (K _{cw} only)	0.71	0.71
Sand Content vs Gamma Log	0.72	0.72

All of the above correlations have a wide scatter of data such that their use to estimate geotechnical parameters cannot be recommended in their present form.

A preliminary editing of the data (removing 14 out of 217 points) improved the correlation between Neutron Porosity vs moisture content from 0.23 to 0.52. This indicates that a detailed review and segregation of the data may significantly improve the correlations.

It is recommended that the four correlations above be examined with more data to determine whether stronger correlations can be established.

Additional correlations between geotechnical parameters such as effective shear strength, in situ densities for spoil and tailings and elastic moduli should be studied with the different geophysical logs.

7.3 Hydrogeologic - Coal

The conclusions are:

- . Preliminary regression analyses carried out for this study indicates that hydraulic conductivity of coal cannot be effectively estimated on the basis of the geophysical log parameters tried.
- . The poor relationship between hydraulic conductivity and geophysical logs may be due in part to the development of the data set used for analyses. A large number of assumptions and arbitrary decisions were made in selecting the data which could have had an influence on these results.
- . Firm conclusions could not be drawn because of the small data set. This was especially true where data were combined into multiple parameter models for evaluation. There were simply too many missing values in the data set. More data is required to confirm results.
- . The retrieval of existing data for hydrogeologic correlations proved to be a more difficult exercise than anticipated. Much of the data was in a form that could not be easily transferred to computer programs for analyses. This resulted in a much smaller usable data set than was originally hoped for.
- . The weak relationships that are indicated suggest that the density, focussed electric and neutron logs give the most promising correlations. However, more analyses should be carried out and none of the logs should be discounted yet.
- . From observations of the plots, there appears to be two fields of data groupings, one for the coal and the other for the noncoal. This suggests that each should be evaluated separately because the rules of the one may not necessarily apply to the other.
- . In this study, the actual geophysical log values were chosen, without any manipulation or filtering except for averaging, to represent the screened depth interval for correlations. It is realized that these average log values reflect the influence of adjacent beds which may be of a different lithology. Greater care must be taken in future studies to ensure that geophysical log values are not averaged over different lithologic units.

Analysis of existing data sets should continue. The recommendations are:

- . Additional analyses for coal should be carried out on existing data to further develop the data set used in the correlations. Greater refinement of both the hydraulic conductivity and geophysical log values needs to be explored.
- . The data set used for correlations should be increased in size from existing data.
- . Correlations should be attempted for sandstone and mudstone data sets.
- . Priority should be given to completing correlations for hydraulic conductivity. However, if time permits, then correlations for the other hydrogeologic parameters, water table, pore pressure and fluid conductivity should be evaluated.

Future work is recommended.

- . Tighter control is required for piezometer well completion. Existing hydrogeologic data shows that often the screen and sand pack were not properly aligned with the aquifer zone, making it difficult to determine the correct depth interval that should be used from the geophysical logs.
- . During geophysical logging, measurements of the physical properties that might influence values on the logs should be taken. For example, drilling fluid conductivity, drilling fluid density, and hole diameter should be recorded so that corrections can be properly applied.
- . For collection of new data, a full suite of geophysical logs should be run. Logs should include plots from both high bed resolution, shallow penetrating and low bed resolution, and deep penetrating tools.

8. REFERENCES

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APPENDIX 1

PROJECT ORGANIZATION AND MANAGEMENT

APPENDIX 1

1. Management Committee

The project is governed by a Management Committee that provides overall direction to the Hydrogeological and Geotechnical Committees conducting the study. This includes responsibility for project content and budget control, as well as responsibility for selection of the final technical and expert committee members.

The following individuals have been appointed to the Management Committee:

- A. Hickinbotham, TransAlta Utilities Corporation (Chairman)
- D. Scott, Civil Engineering Department, University of Alberta
- E. Fraser, Suncor Inc.
- N. Wade, Monenco Consultants Limited
- G. Jenkins, Chairman, Geotechnical Committee, Manalta Coal Limited
- L. Pitts, Chairman, Hydrogeological Committee, Monenco Consultants Ltd.
- T. Sneddon, Alberta Office of Coal Research & Technology
- B. Das, CANMET: Energy, Mines & Resources, Canada

2. Geotechnical Committee

This committee is responsible for the scope of the geotechnical component of the study, technical procedures, and for making recommendations to the Management Committee with regard to selection of competent geophysical and geological professionals to conduct the research.

The following representatives comprise the Geotechnical Committee:

- G. Jenkins, Manalta Coal Ltd., (Chairman)
- B. Das, CANMET: Energy, Mines & Resources, Canada
- F. Khan, Terracon Geotechnique Ltd.
- N. Wade, Monenco Consultants Limited

3. Hydrogeological Committee

Similarly, the Hydrogeological Committee is responsible for the scope and procedures within the hydrogeological component of the study.

The committee is comprised of the following representatives:

- L. Pitts, Monenco Consultants Ltd. (Chairman)
- N. Worsley, Saskatchewan Power Corporation
- T. Dabrowski, Piteau Associates Engineering Ltd.
- L. Nichols, Terracon Geotechnique Ltd.
- G. Lobb, Syncrude Canada Ltd.
- J. Pawlowicz, Alberta Research Council

4. Project Manager

The administration of the project and coordination of subcontractors is carried out by the Coal Mining Research Company acting as project manager, under the direction of the Management Committee. Additional responsibilities include technical and financial

progress reports to the Management Committee, as well as preparation of project reports.

5. Expert Review Panel

The expert review panel has been selected to review the results of the research conducted during the project and to advise on the content and procedures required in subsequent phases. Panel members include:

S. Keys	United States Geological Survey, Denver, Colorado. (Retired)
P. Killeen	Geological Survey of Canada
J. Mwenifumbo	Geological Survey of Canada
C. Brawner	University of British Columbia
N. Morgenstern	University of Alberta
R. Bishop	BFB Instruments, (Canada) Ltd.

APPENDIX II

BPB GEOPHYSICAL TOOLS



SONDE MEASUREMENTS

— SUMMARY (of subsurface leaflets 1 to 14)

FIELD INSTRUMENTATION

SUBSURFACE
No. A

Key:

- STANDARD
- STANDARD with ALTERNATIVE OPTION
- ALTERNATIVE TO ■
- 1 Single arm caliper
- 2 Three arm caliper

MEASUREMENT (S)

MNEMONIC CODE	LEAFLET No.	SONDE DIMENSIONS													
		MAXIMUM DIAMETER mm (ins)	LENGTH m (ft)	GAMMA RAY	CALIPER	LONG SPACED DENSITY (>30 cm)	INTERMEDIATE SPACED DENSITY (20-30 cm)	SHORT SPACED DENSITY (<20 cm)	COMPENSATED DENSITY	LONG SPACED NEUTRON (>30 cm)	SHORT SPACED NEUTRON (<30 cm)	COMPENSATED NEUTRON	SONIC (20, 20, 40 & 60 cm spacings)	RESISTANCE (Single Point)	SPONTANEOUS POTENTIAL
DD1	1	48 (1 7/8)	3.50 (11.5)	●	●	●	●	●							
MS1	2	51 (2)	3.38 (11.1)										●		
SR1	3	60 (2 3/8)	2.39 (7.8)												
RO1	4	38 (1 1/2)	2.76 (9.0)												
DR1	5	48 (1 7/8)	3.50 (11.5)	●	●	●							□	■	
DD2	6	38 (1 1/2)	2.45 (8.0)	●		●	□	■							
NO1	7	38 (1 1/2)	2.41 (8.0) or 2.13 (7.0)						■	□					
VO1/2	8	42 (1 11/16)	2.63 (8.6)												
DV1	9	51 (2)	4.50 (14.8)												
DV2		64 (2 1/2)	5.30 (17.4)		●										
TT1	10	38 (1 1/2)	1.45 (4.8)												
CO1	11	38 (1 1/2)	1.90 (6.3)		●										
RS1	12	33 (1 1/8)	1.48 (4.8)										●	●	
NN1	13	38 (1 1/2)	2.47 (8.1)	●						●	●	●			
DD3	14	48 (1 7/8)	3.50 (11.5)	●	●	●	●	●							

TEMPERATURE (ABSOLUTE, DIFFERENTIAL, DIFFERENCE)
HOLE DEVIATION (TILT AND AZIMUTH)
FORMATION DIP (DIP AND AZIMUTH)
SEISMIC REFERENCE SURVEY
VERTICAL SEISMIC PROFILING

ADDITIONAL SERVICES

BPB's major slimline sondes and measurements, as summarised on the previous page, are described in some detail in the following 'subsurface' leaflets. This equipment offers a broad range of options to allow the selection of logging suites tailored to suit both application and hole condition. Such equipment is readily available out of most BPB operating centres.

These measurements may, however, be augmented by additional equipment offered on a more limited basis. Although not exhaustive, the following list will provide an indication of a few of these additional services. Some mobilisation notice is usually required.

- | | |
|-------------------------------|---|
| — Casing Collar Locator (CCL) | — available in combination with a BPB single function Gamma Ray sonde. |
| — Sidewall Sonic | — for stationary measurements of 'S' wave velocities. |
| — Cement Bond Log (CBL) | — with either simple Amplitude or Variable Density (VDL) output. |
| — Spectral Gamma | — a basic four channel device for Ur, K, Th + Total Count, based on a BPB single function Gamma Ray sonde. |
| — Flowmeter | — available to suit a variety of hole diameters. |
| — Magnetic Susceptibility | — |
| — General Specifications | — the nominal Temperature and pressure specifications, as stated in the sonde leaflets, can often be uprated to meet specific borehole conditions or client requirements. |

BPB welcome enquiries relating to the possible provision of any further slimline logging equipment and services not listed or specified herein.



DD1 DUAL DENSITY, GAMMA RAY, CALIPER, SONDE. (OR COAL COMBINATION SONDE CCS)

FIELD INSTRUMENTATION
SUBSURFACE No. 1

MEASUREMENTS:

LONG SPACING DENSITY (LSD)
BED RESOLUTION DENSITY (BRD)
COMPENSATED DENSITY
GAMMA RAY
CALIPER

The DD1 Sonde has been designed for the full range of borehole diameters, depths and conditions generally associated with slimhole drilling. All logs are recorded in a single run, with a selection of processing and presentation options available to suit specific requirements.

GENERAL SPECIFICATIONS:

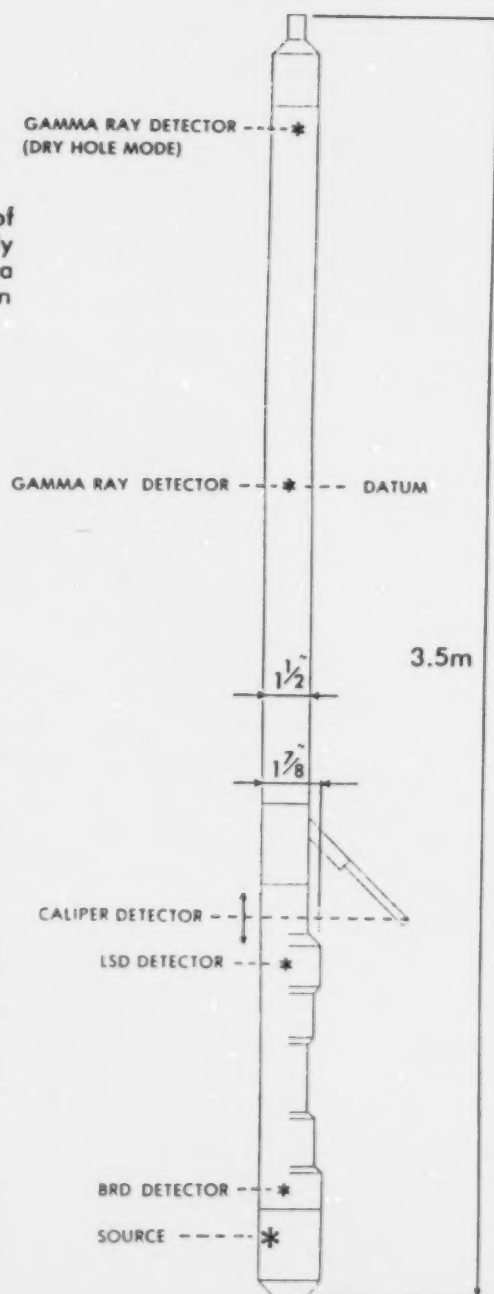
Length — 3.5 m (11.5')
Weight — 20 kg (44 lbs)
Diameter — 4.8 cm (1 7/8") max
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000m (6500')
Hole Diameter — open hole: 6.5 to 30 cm (2.5" to 12")
casing or rods: 5.5 to 30 cm (2.0" to 12")

Logging Speed — standard logging: 9m/min (30'/min)
— detail logging: 2.25m/min (7.5'/min)
Logging Mode — Sidewall, Caliper eccentricised

Optimum calibration requires open, fluid filled holes with diameters less than 20 cm (8"). Results of a more qualitative nature will be obtained through casing or drill rods and/or without fluid. Significant caving of the borehole wall will adversely affect results.



DD1 SCHEMATIC

TECHNICAL INFORMATION:

GAMMA RAY — Measurement of naturally occurring radioactivity utilizes an uncollimated Sodium Iodide Crystal coupled to a Photo Multiplier Tube based amplifying system. Calibration, by active field jig allows linear presentation in API units with borehole correction. Some sondes offer a remote detector position option, to prevent interference from the source in dry holes.

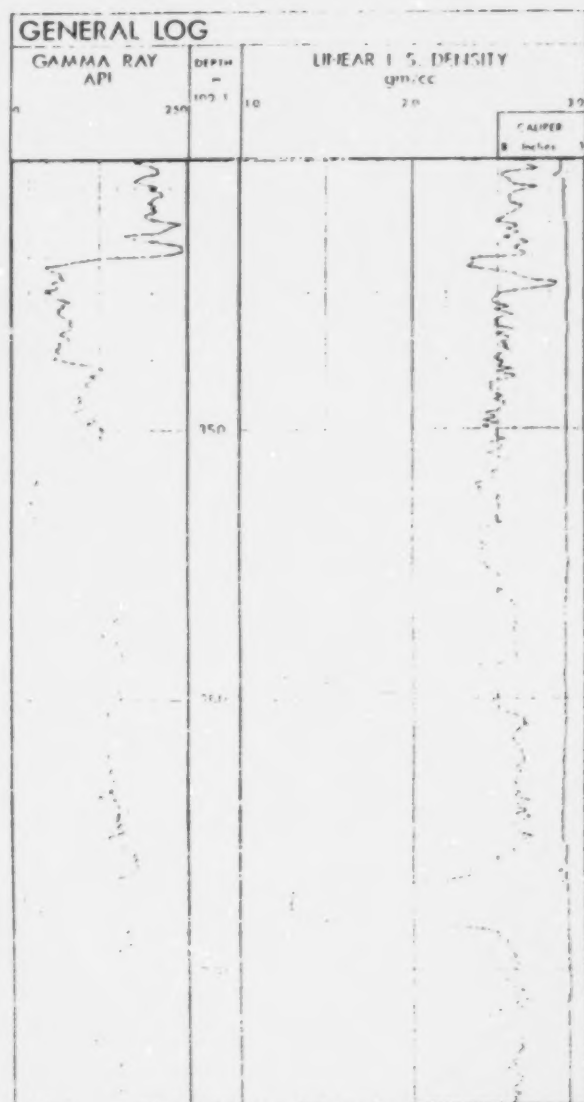


Fig. 1 — LINEAR DENSITY GENERAL SCALE.

CALIPER — A single arm electro mechanical device is held closed for entry into the borehole and activated during the logging run. Field calibration produces a precise linear measurement of hole diameter and caving profile. Hole diameter ranges:

- Standard arm 4.8 to 20 cm (1 7/8" to 8")
- Long arm 4.8 to 30 cm (1 7/8" to 12")

SOURCE — A doubly encapsulated sealed source of Caesium 137 at an activity of 100 mCi. is mounted within a sidewall collimated holder and locked securely to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 10 mrem/hr.

DENSITY — Measurement of scattered radiation levels is made with two independent detecting systems, both similar to the Gamma Ray detector but incorporating crystal shielding (sidewall collimation) and cable deadtime correcting circuitry. Calibration utilizes large passive base facilities and active field jigs to allow log presentation in gm/cc.

LSD — The deeper reading device, with a source to detector spacing of 48 cm (19"), provides the definitive density log in most borehole conditions and is presented:

- with linear response, facilitating full 1-3 gm/cc range evaluation,
- and/or — with logarithmic response, enhancing the 1-2 gm/cc range.

Borehole corrections are applied and compensation is available, incorporating the BRD, to improve density measurement in difficult hole conditions.

BRD — With a spacing 15 cm (6") this shallower reading measurement produces an essentially linear response density log as both:

- an independent high resolution log for precise boundary definition. Digital and Deconvolution Filter options can, under ideal conditions, provide resolution enhancement down to 5 cm (2").
- on LSD compensation factor.

PRESENTATION:

Logs are recorded in Metric or Imperial units and presented on a standard 6 track API logging chart with full flexibility of scales and format. 'General' vertical scales range upwards from 100:1 whilst 'Detail' scale options, reserved for closer investigation of zones of interest, range down to 10:1. Some of the more usual presentations include:

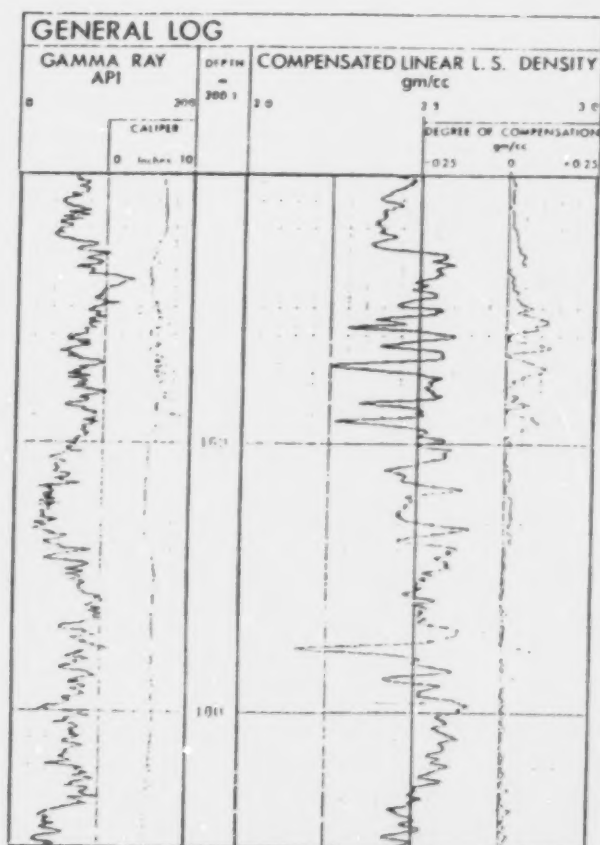


Fig. 2 — COMPENSATED DENSITY GENERAL SCALE.

LINEAR DENSITY — GENERAL SCALE (fig. 1)

Linear LS Density over a range of either 1-3 gm/cc or 2-3 gm/cc depending on density range encountered.

Linear Gamma Ray and Caliper on suitable scales.

LOGARITHMIC DENSITY — GENERAL SCALE

As fig. 1 except that the LS Density is presented with logarithmic response to provide enhancement over the 1-2 gm/cc range.

COMPENSATED DENSITY — GENERAL SCALE (fig. 2)

Similar to fig. 1 except that the LS Density is compensated by the BR Density and the 'degree of compensation' included.

DETAIL DENSITY — DETAIL SCALES (fig. 3a, b, c)

A comparison of the three density options: LSD Linear, LSD Logarithmic and BRD (Linear), on detail scales; an illustration of scale flexibility and tool performance through seams or zones of interest over the full 1-3 gm/cc range.

Density correction and processing options vary according to the computational power of the surface equipment and may be summarized as follows:

Corrected/Processed for the effects of:	Surface Equipment		
	Standard Unit	Log Processor Unit	Computer Graphics Unit
Borehole diameter	Yes	Yes	Yes
Fixed 1.0 gm/cc mud weight	Yes	—	—
Mud weight as input	—	Yes	Yes
Formation Z/A effect	Yes	Yes	Yes
Detector deadtime	Yes	Yes	Yes
Cable deadtime	Yes	Yes	Yes
LSD Linearization option	No	Yes	Yes
LSD Compensation (with BRD) option	No	Yes	Yes
BRD Deconvolution option	No	Yes	Yes
Gamma Ray Stripping	No	No	Yes
Variable Caliper measuring point	No	No	Yes

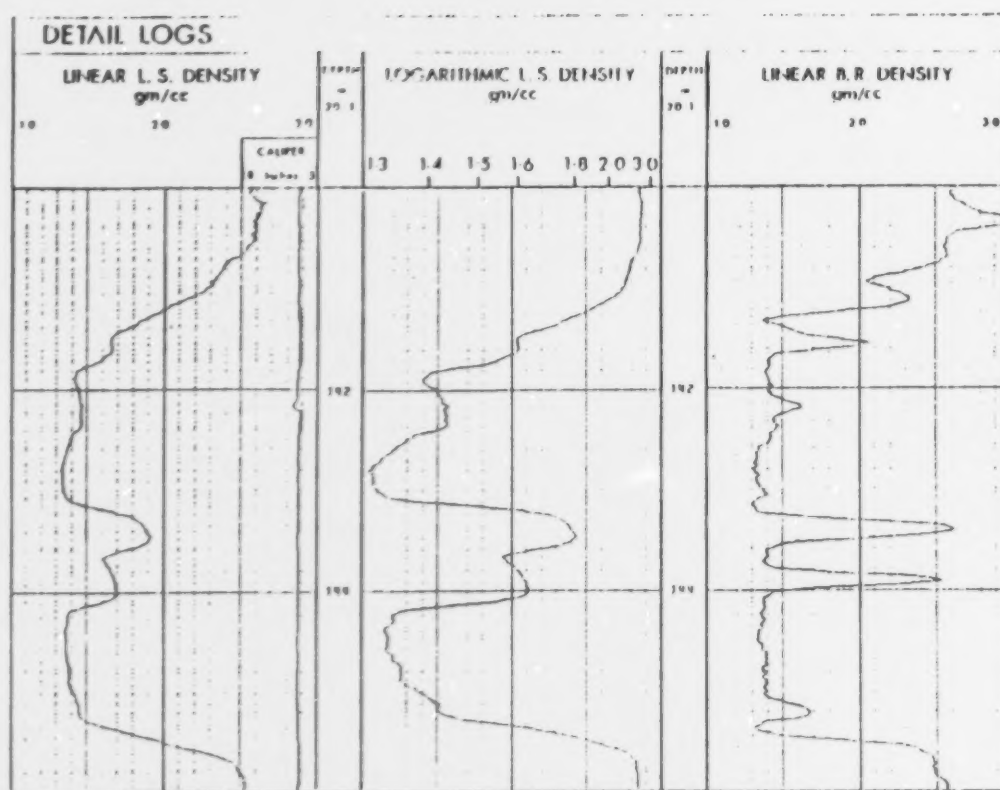


Fig. 3 — DETAIL SCALE DENSITY PRESENTATION OPTIONS.

APPLICATION SUMMARY:

GAMMA RAY — Shale Content, Lithology Identification and Correlation.

DENSITY : LSD — Porosity, Lithology Identification and Correlation plus quantitative evaluation of: Lithology, Formation Properties, and Strength Index (with MC Sonic Sonde).

: BRD — Precise boundary definition usually to ± 2 cm (plus LSD compensation).

CALIPER — Borehole diameter and caving profile (plus sidewall configuration and density correction).

The DD1 suite is seen as a basic slimhole evaluation package, providing both general lithology and detailed seam information in one logging run. Additional sonde runs are available to complement the DD1 service according to specific interpretation requirements.

REFERENCES:

Further information on many aspects of the DD1 service may be found in the following BPB publications, available on request.

1. BPB Coal Interpretation Manual
2. The Radiation Density Log Applied to the Resolution of Thin Beds in Coal Measures — J.R. Samworth
3. Slimline Dual Detector Density Logging, a Semi-Theoretical but Practical Approach to Correction and Compensation — J.R. Samworth

MEASUREMENTS:

ACOUSTIC VELOCITY LOGS AT:

- 20cm (8") RESOLUTION, DESPIKED
- 40cm (16") RESOLUTION, DESPIKED
- 60cm (24") RESOLUTION, DESPIKED
- 20cm (8") RESOLUTION, UNPROCESSED

PLUS INTEGRATED SONIC LOG

The MS1 Sonde provides high quality Sonic Transit Velocity data, within a slim diameter and at a variety of vertical resolutions, throughout a comprehensive range of borehole diameters and conditions.

GENERAL SPECIFICATIONS:

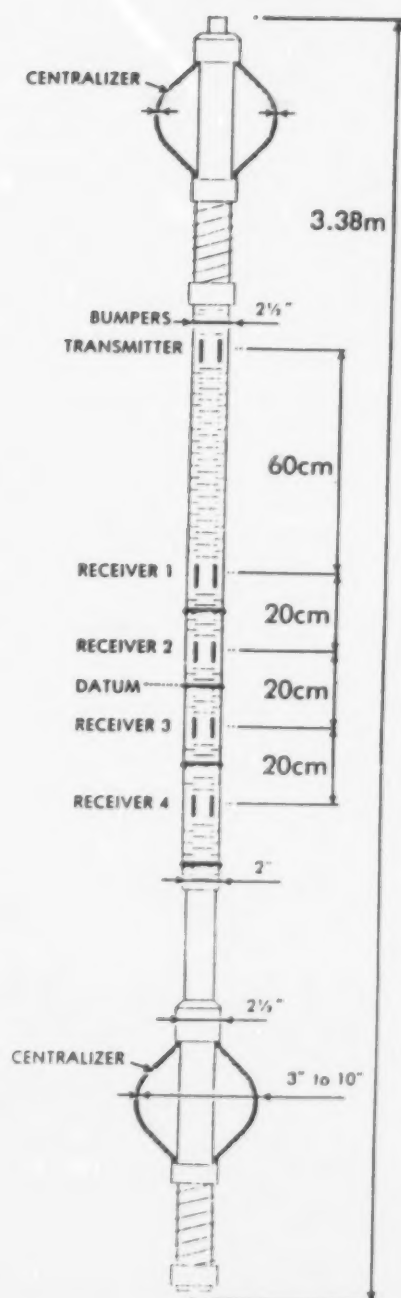
- Length — 3.38m (11.1')
- Weight — 16kg (35 lbs) without centralizers
22kg (49 lbs) with centralizers
- Diameters — basic sonde — 51mm (2")
— with bumpers/centralizers 65mm (2.5")
- Temperature — up to 70°C (158°F)
- Pressure — up to 210 kg/cm² (3000 psi)

OPERATING CONDITIONS:

- Hole Depth — to a max. of approx. 2000m (6500')
- Hole Diameter — 65mm (2.5") to 90mm (3.5") without centralizers
— 90mm (3.5") to 300+ mm (12+ ") with centralizers
- Logging Speed — Standardly: 9m/min (30' /min)
- Logging Mode — Centralized, where borehole diameter and conditions permit, with a full 360° window for all 5 transducers (one transmitter and four receivers).

Precise in-built electronic calibration ensures the accuracy of all transit timings, allowing downhole processing of velocity data, prior to surface transmission. Sonic logging will be successful only in Open (Uncased), Fluid Filled boreholes.

Sonic measurements will become problematic in badly caved sections of the borehole or in unconsolidated (or other) formations where adequate acoustic coupling cannot be achieved.



TECHNICAL INFORMATION:

A ceramic transmitter T is fired with a high voltage pulse every 0.1 sec. causing acoustic energy to enter the formation, via the borehole fluid (essential for efficient coupling), as a compression wave. Fig. 1.

Receivers R1, R2, R3, R4 are successively stimulated by this same compression wave after passing through sections of the formation between the transmitter and appropriate receiver. The distance between each of the receivers is fixed, and of course known precisely. Consequently measurement of the time taken for the wave to pass between receiver pairs will enable the calculation of its velocity, normally known as the Sonic Velocity.

By incorporating pre-programmed microprocessors in the sonde various combinations of receiver pairs can be selected and processed simultaneously. The following options are standardly available:

- R1-R2 20cm (8") — HIGH RESOLUTION CHANNEL No.1
- R2-R4 40cm (16") — MEDIUM SPACING CHANNEL No. 2
- R1-R4 60cm (24") — LONG SPACING CHANNEL No. 3
- R3-R4 20cm (8") — DISCONTINUITY CHANNEL No. 4

The MS1 Sonde calculates each of these four velocities every 0.1 sec. (equivalent to 1.5cm at the standard 9m/min. logging speed), transmitting results for surface recording as continuous depth based logs.

Discontinuities in the formation can often cause interruption to the compression wave, causing unwanted spikes on the log. In Channels 1, 2 and 3, these effects have been identified and removed, again by the use of downhole microprocessors. Channel 4 is presented in its original unprocessed form, providing both a quality control on the processed channels and also a means of identifying zones of high discontinuity, eg fracture detection.

System design ensures that the first arrival of the compression wave at all receivers results, in normal conditions, from transit paths through the formation rather than through the body of the sonde or through the borehole fluid. Limiting extremes of borehole diameter and formation velocity combinations, beyond which 'first arrival' problems will be encountered, are listed in the Application section.

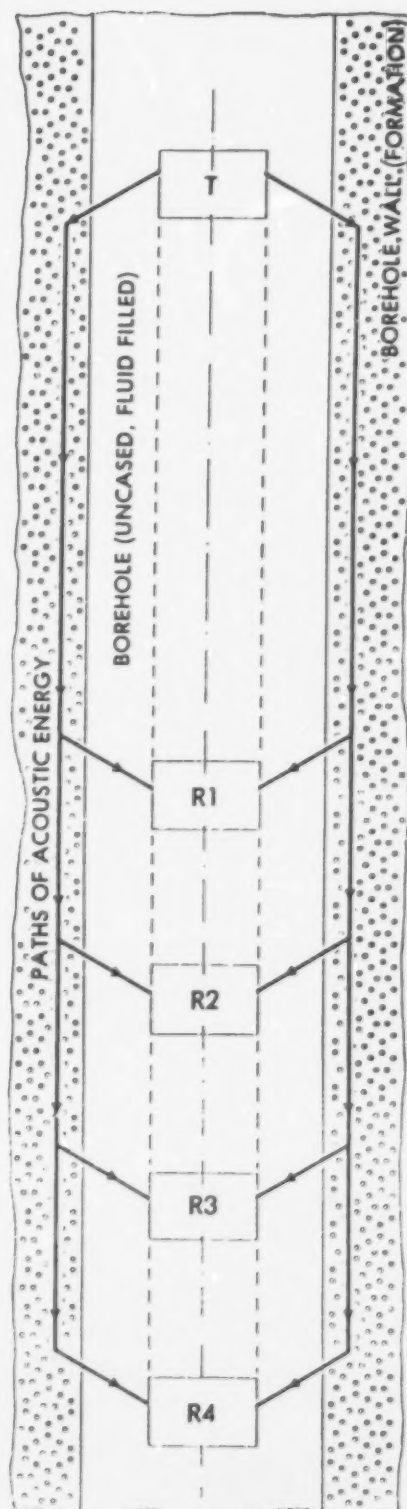


Fig. 1 — TRANSDUCER SCHEMATIC

PRESENTATION:

A full flexibility of vertical scales (either metric or imperial) and presentation formats is available, to include up to all four Velocity Channels and Integrated data.

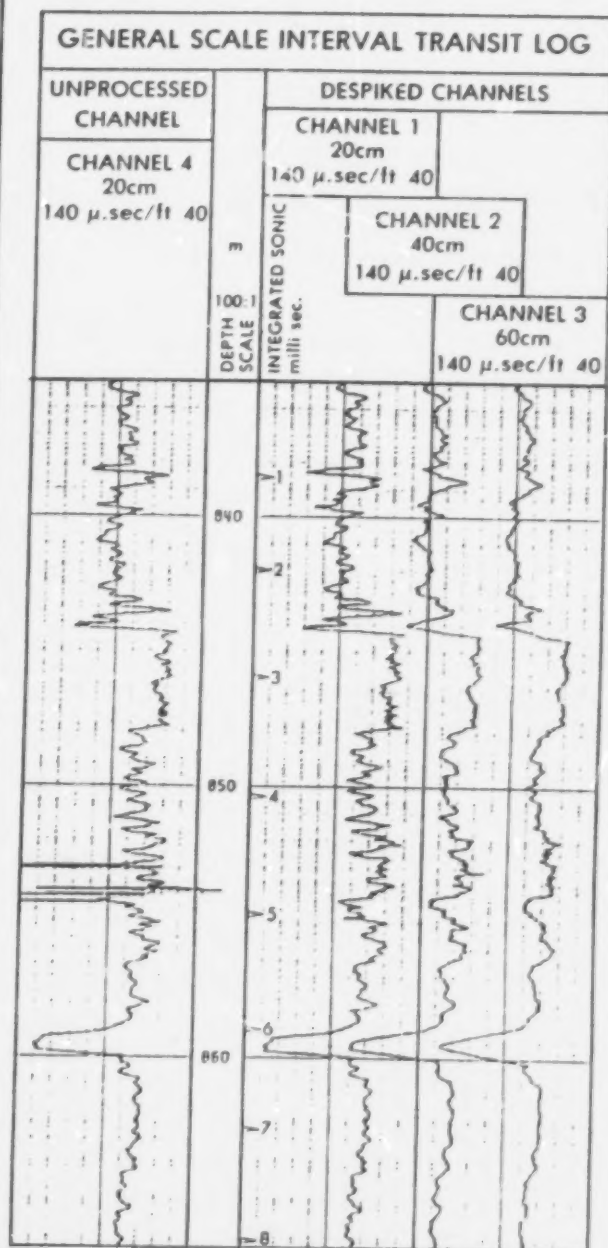


Fig. 2 is a comprehensive illustration of all Velocity logs, together with a Channel 2 based Integrated Sonic log, at a 100:1 metric scale.

The 'spiking' effects of discontinuity or other features can be readily seen in this example. Channel 4, within the 853-855m interval, contains spiking features which have been automatically identified as geophysically invalid and processed out of the remaining channels.

Fig. 2 — PRESENTATION EXAMPLE

- Notes:
- Velocity logs are usually presented in either μ .sec/ft or μ .sec/m.
 - The Integrated Sonic Log, based on any of the Velocity Channels, is available as a surface processing option.
 - A Channel 1 deconvolution option is available as a surface processing procedure to further enhance the resolution of this high resolution channel, from 20cm to 14cm.

APPLICATION SUMMARY:

- | | |
|---|--|
| LONG SPACING (60cm)
CHANNEL No. 3 | — provides the best average formation velocity and minimises the effects of any cavings. This channel is ideal for porosity determination, lithology determination, correlation, forming an integrated sonic log for seismic correlations and for combining with a density log for rock strength determinations. |
| HIGH RESOLUTION (20cm)
CHANNEL No. 1 | — is suitable for delineation of bed boundaries and structures within the seams. The high resolution allows more detailed analyses of rock strength and seam quality. Deconvolution options offer further resolution enhancement. |
| MEDIUM SPACING (40cm)
CHANNEL No. 2 | — is required when borehole conditions, mainly because of caving, preclude the use of the HR Channel. This spacing is often preferred in narrow diameter boreholes to the LS Channel as more detail is displayed. |
| DISCONTINUITY (20cm)
CHANNEL No. 4 | — monitors the original unprocessed signal and is thus useful for indications of fractures and other conditions likely to produce spiking effects. |
| INTEGRATED SONIC | — Usually derived from either the LS or HR Channel, depending on hole condition, and used as an aid for seismic interpretation. |

N.B. All four channels are valid for rock velocities down to 150 μ .sec/ft in holes up to 10" diameter. Additionally for the same range of rock velocities channel 2 is valid up to 13" diameter and channel 4 up to 16".

REFERENCES:

- Further information on the MS1 Service may be found in the:
- BPB Coal Interpretation Manual,
a BPB publication available on request.

SR1 SEISMIC REFERENCE SONDE.

MEASUREMENTS:

MEAN TIMES mSec
CORRECTED 2-WAY TIMES mSec
AVERAGE VELOCITY m/sec TO SPECIFIC HORIZONS
INTERVAL VELOCITY m/sec BETWEEN HORIZONS
RMS VELOCITY m/sec

The SR1 Sonde and SRS Survey Panel can be set up with a winch unit as a stand alone service. In this case the normal BPB Slimline Logging Unit is not required on site.

GENERAL SPECIFICATIONS:

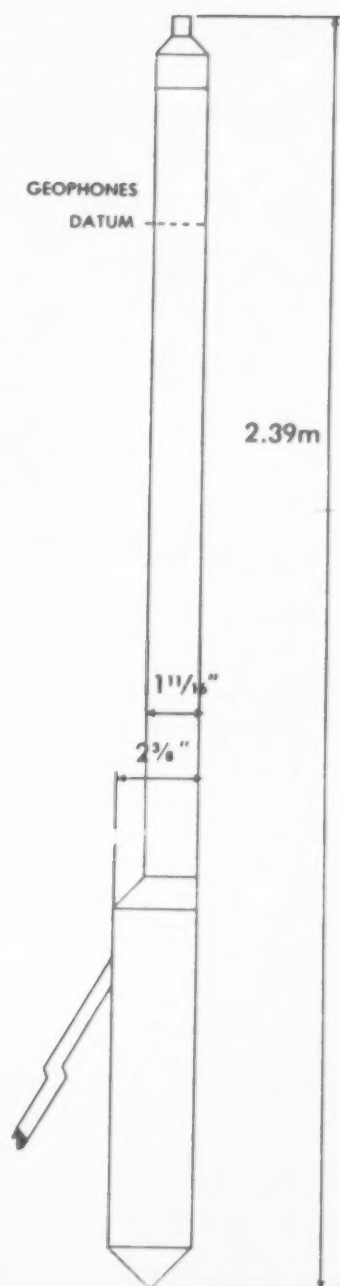
Length	— 2.39m (7.8')
Weight	— 20Kg (45lbs)
Diameter	— 6cm (2 3/8")
Temperature	— up to 70°C (158°F)
Pressure	— 492Kg/cm ² (7,000psi)

OPERATING CONDITIONS:

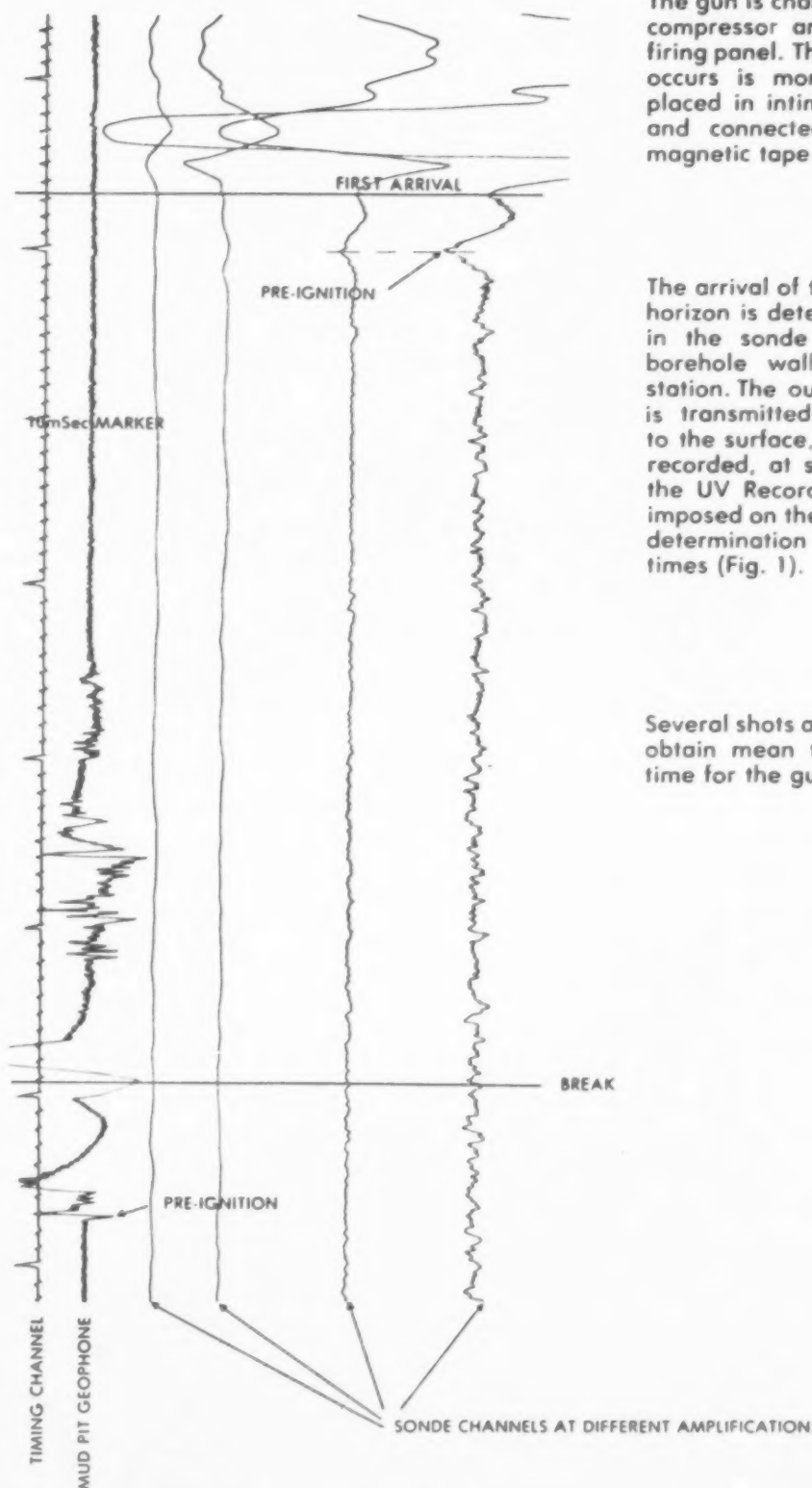
Hole Depth	— to max. of approx. 3,050m (10,000')
Hole Diameter	— 7.5cms to 33.0cms (3" to 13")

Optimum results require open fluid filled holes but good results can usually be obtained in dry or cased holes.

The BPB airgun requires a fluid filled pit 2mx2mx2m (6'x6'x6') for efficient acoustic coupling. The airgun may be replaced by the client's own wave propagating device or explosives.



TECHNICAL INFORMATION:



The gun is charged by a high pressure air compressor and triggered by a remote firing panel. The time at which detonation occurs is monitored by a hydrophone placed in intimate contact with the gun and connected to a UV recorder or magnetic tape.

The arrival of the compression wave at a horizon is detected by a geophone array in the sonde which is locked to the borehole wall at the required depth station. The output signal from the sonde is transmitted via the logging cable to the surface, where the wave train is recorded, at several different gains, on the UV Recorder. Timing lines are also imposed on the output to ensure accurate determination of the required travel times (Fig. 1).

Several shots are taken at each horizon to obtain mean times. A typical recharge time for the gun being 1 minute.

CORRECTIONS:

The recorded seismic times are corrected using the following time correction factor t_e , to allow for the different depths of the weathering, the gun depth, the elevation of ground level above the seismic datum, the gun and hydrophones separation together with the various velocities involved near surface is given by:

$$t_e = \frac{h}{V_w} - \frac{(dw - dg)}{V_{we}} - \frac{(EGL - dw)}{V_e}$$

Where h is the separation of gun and hydrophone
 V_w is the mud pit fluid velocity
 dw is the weathering depth below ground level
 dg is the gun depth below ground level
 EGL is the elevation of the SRS datum above the seismic datum
 V_{we} is the weathering velocity
 V_e is the elevation velocity

V_e , the elevation velocity, is:

= V_{we} if $EGL < dw$
 = velocity of first layer below dw if $EGL > dw$.

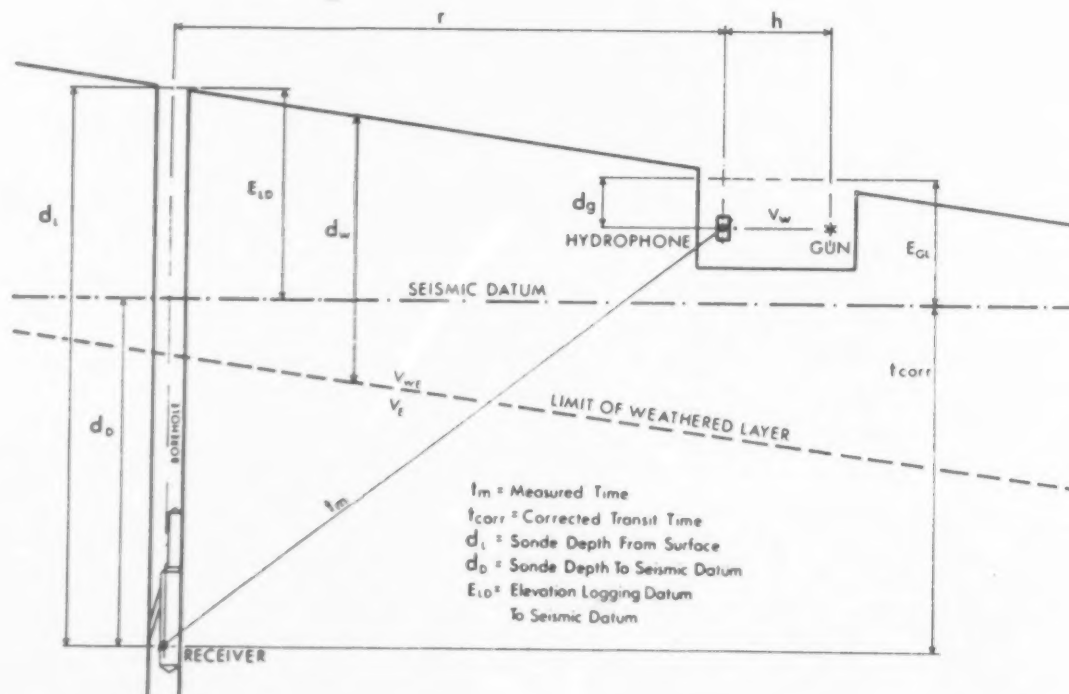


Fig. 2 SEISMIC REFERENCE SURVEY SCHEMATIC

PRESENTATION:

Logged Depth m	Measured Times m sec	Mean Times m sec	Depth below Seismic Datum m	Corrected 2 Way Times m sec	Average Velocity m sec	Interval Velocity m sec	R M S Velocity m sec
32.20	25.75	25	32.20	34.6	1860.7	1860.7	1860.7
466.00	187.187	187	466.00	378.3	2463.4	2524.1	2470.9
488.69	191.191	191	488.69	386.5	2529.1	5589.9	2575.5
718.45	239.239	239	718.45	483.1	2974.3	4754.4	3135.0
801.00	265.265	265	801.00	535.2	2993.3	3169.1	3138.4
842.00	278.278	278	842.00	561.2	3000.5	3148.9	3138.9
875.39	286.286	286	875.39	577.3	3032.8	4164.2	3171.8
925.00	302.302	302	925.00	609.3	3036.2	3096.8	3167.9
989.00	318.318	318	989.00	641.4	3084.0	3993.3	3214.2
1060.00	336.337	336.5	1060.00	678.4	3124.9	3832.7	3251.0
1106.9	352.352	352	1106.96	709.4	3170.6	3027.4	3241.6

Fig. 3 TABULATED DEPTHS AND VELOCITIES

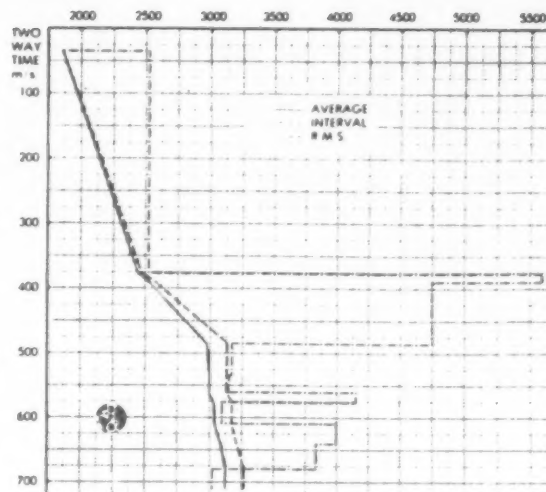


Fig. 4 PLOT OF AVERAGE INTERVAL AND RMS VELOCITIES VS TWO WAY TIME

Interpolated Depths m	2 Way Times m sec	Interpolated 2 Way Times m sec	Depths m
50	48.8	50	51.6
100	98.6	100	114.7
150	127.9	150	177.8
200	167.6	200	240.9
250	207.2	250	304.0
300	246.8	300	367.1
350	286.4	350	430.2
400	326.0	400	520.9
450	365.7	450	639.8
500	391.2	500	745.2
550	412.2	550	824.3
600	433.3	600	910.6
650	454.3	650	1005.5
700	475.3	700	1092.7
750	500.0		
800	534.6		
850	565.1		
900	593.2		
950	621.8		
1000	647.1		
1050	673.2		
1100	704.8		

Fig. 5 TABULATED INTERPOLATED DEPTHS AND TWO WAY TIMES

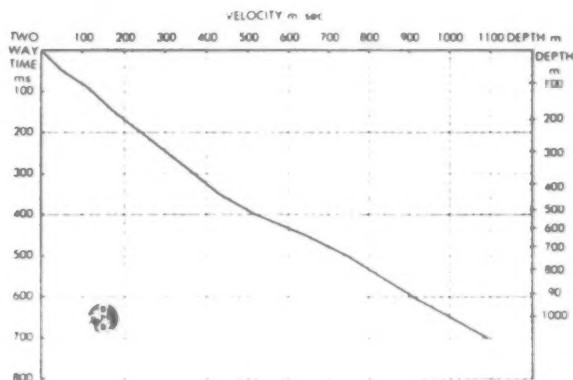


Fig. 6 PLOT OF TWO WAY TIME VS DEPTH

APPLICATIONS:

Accurate conversion from depth to seismic time and vice versa. The data can also be used to correct sonic logs, whether for more accurate log interpretation or to enable the depth to time conversion to be performed continuously throughout a borehole. This conversion enables a synthetic seismogram to be produced.

RO1 FOCUSSED ELECTRIC SONDE

(OR FE MK II SONDE)

**FIELD
 INSTRUMENTATION**

**SUBSURFACE
 No. 1**

MEASUREMENTS:

FORMATION RESISTIVITY

The RO1 Sonde is a single function 3 electrode laterolog device combining high power of vertical resolution and intermediate depths of investigation. The result is a quantitative measure of formation resistivity well suited to the interpretation of formation properties in slim holes.

GENERAL SPECIFICATIONS:

Length	— 2.76m (6.5') Sonde
	— 12.3m (40.4') Sonde + Bridle (Standard)
	— 7.3m (24') Sonde + Bridle (Shallow hole)
Weight	— 15kg (33lbs)
Diameter	— 3.8cm (1 1/2")
Temperature	— up to 70°C (158°F)
Pressure	— up to 210kg/cm ² (3000psi)

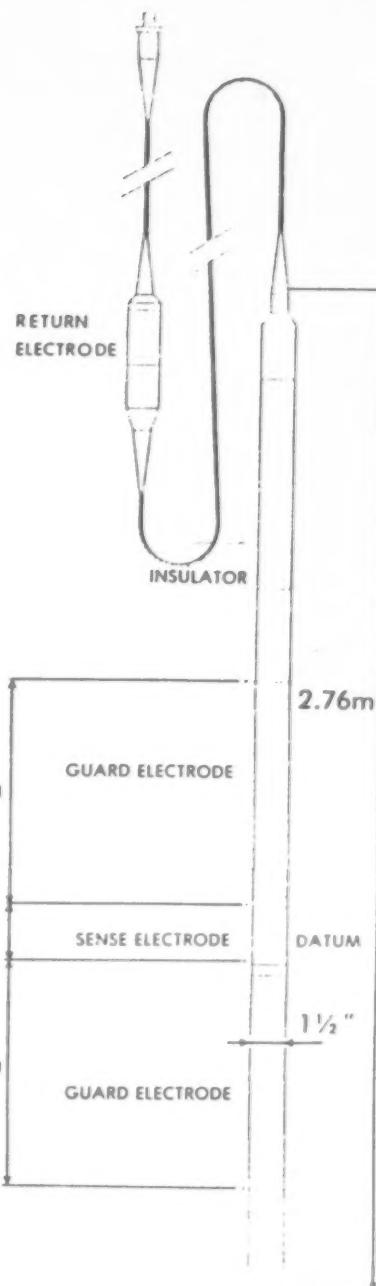
OPERATING CONDITIONS:

Hole Depth	— to a max. of approx. 2000m (6500')
Hole Diameter	— open hole 5.0cm to 25+cm (2.0" to 10+")

Logging Speed	— standardly 9m/min (30' /min)
Logging Mode	— free running
Resistivity range	— 0.2 to 20,000 ohm m

Open, fluid filled holes are a prerequisite, and optimum hole diameters less than 20cm (8"). Fluid resistivities should be as low as possible, this requirement being more important in low resistivity formations.

Logging near the surface is limited by the requirement for the bridle to be in the fluid of the open hole. Excessive borehole casing will adversely affect results.



TECHNICAL INFORMATION:

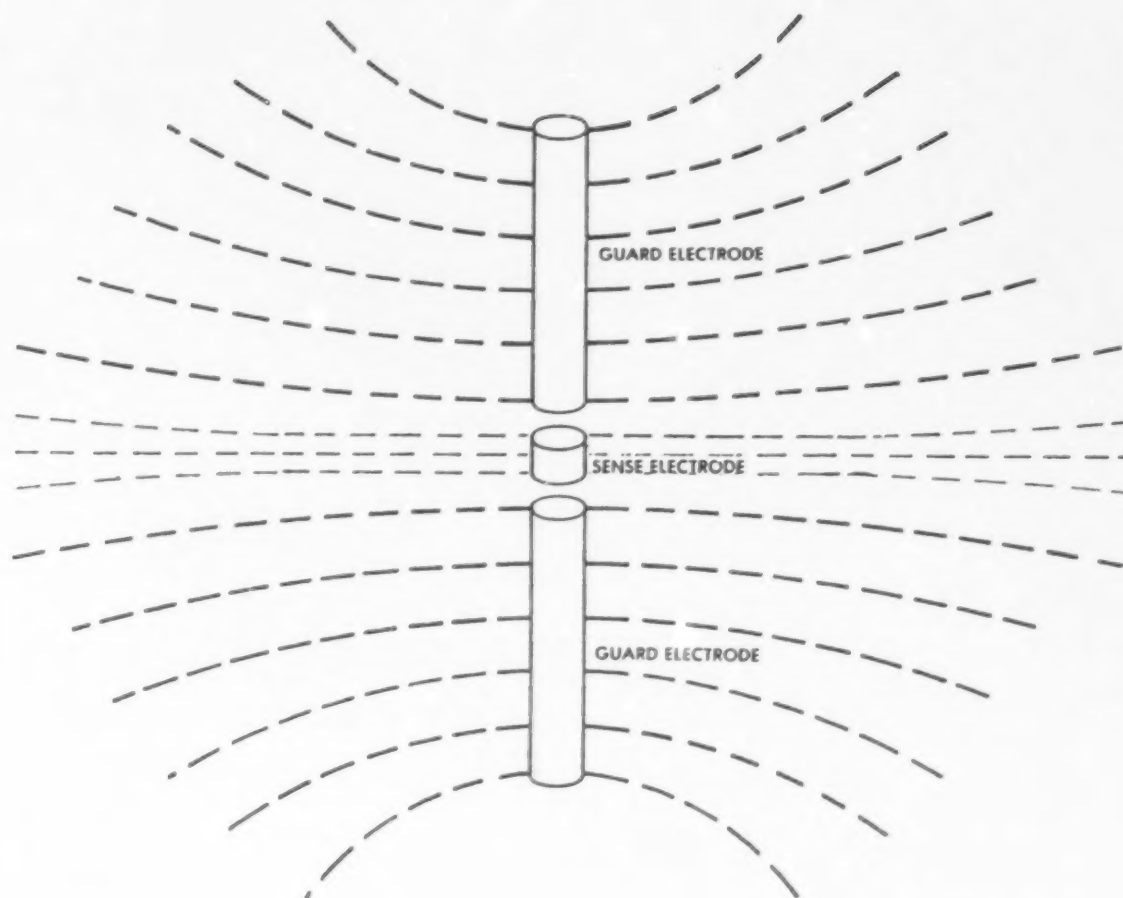


Fig. 1 CURRENT DIAGRAM

An electric current is established from the 'sense' electrode via the borehole fluid into the formation, the circuit being eventually completed through surface electronics and logging cable.

The initial focussing of this current (fig. 1) into a narrow 360° cylindrical disc is achieved with a secondary circuit set up from the two larger 'guard' electrodes, this circuit being completed through a further electrode positioned at an optimum distance above the sonde — although this distance can be decreased if near surface measurement is required.

Sonde electronics hold the potential differences between the sense and guard electrodes at zero, hence the focussing effect, and monitor both the sense current and voltage levels throughout the full range of resistivities encountered.

Combination of these values yield, via Ohm's law, a measure of the resistance seen by the sense electrode. Translation of this resistance into a continuous depth based log of formation resistivity follows, with the application of conversion and correction based on sonde geometry, borehole diameter and mud resistivity — see reference 2.

PRESENTATION:

Logs may be recorded in Metric or Imperial depth scales and are available with a full flexibility of vertical and horizontal scales.

The Focussed Electric measurement is usually presented on a logarithmic scale over several decades, to meet the range of resistivities encountered.

Linear presentation is also available if specifically required.

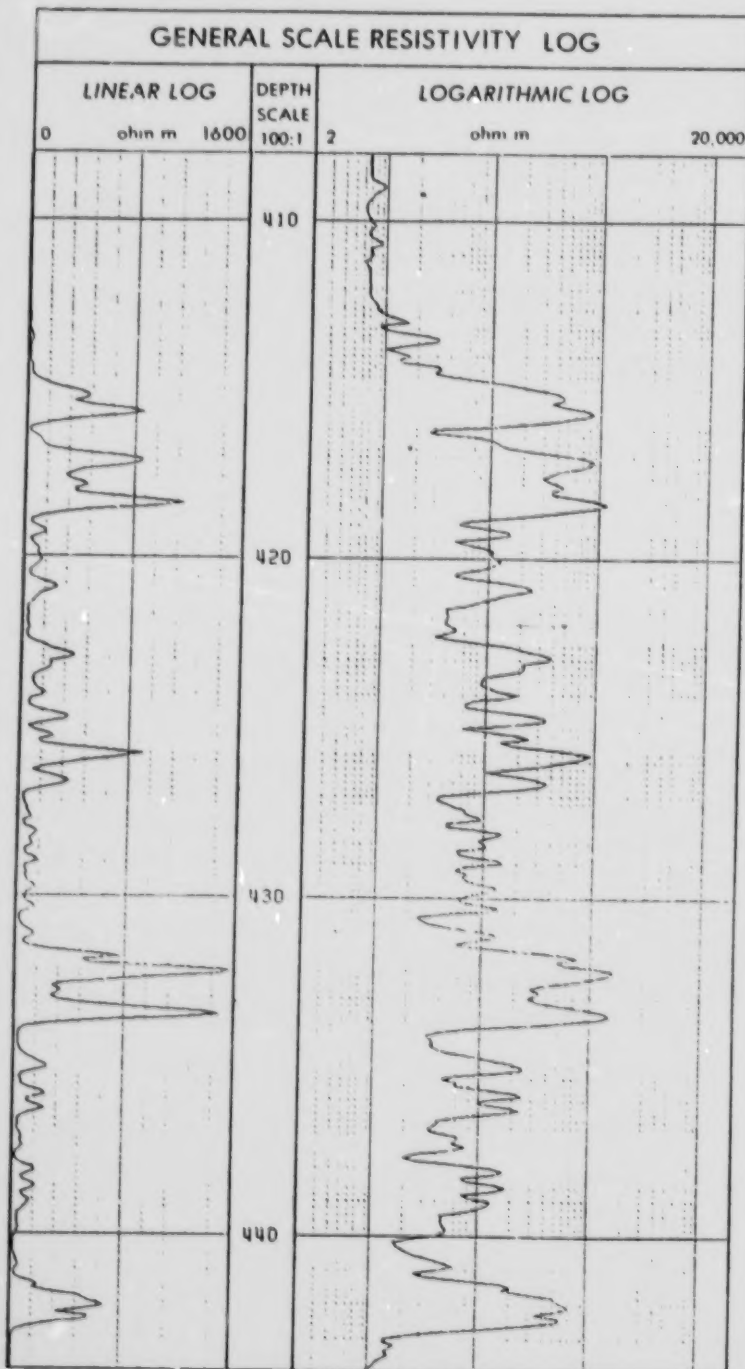


Fig 2 LOG PRESENTATION

APPLICATIONS

The RO1 Sonde's Focussed Electric log of formation resistivity combines the advantages of a Single Point device's high resolution (but uncalibrated) with a Normal or Lateral device's calibration ability (although poor resolution) — whilst maintaining a depth of investigation realistic in terms of slimhole conditions.

The resulting log provides not only valuable lithology correlation data but also a quantitative measure of formation properties to enable further interpretation to be considered.

REFERENCES:

Further information on Focussed Electric measurement may be found in the following BPB publications, available on request:

1. BPB Coal Interpretation Manual.
2. A Focussed Resistivity Tool for Slimline Coal Logging Systems — J R Samworth and M A Cherrie.



DR1 DENSITY, RESISTIVITY, GAMMA RAY, CALIPER, SONDE. (or High Resolution Coal Sonde HRCS)

FIELD
INSTRUMENTATION
SUBSURFACE
No 6

MEASUREMENTS:

BED RESOLUTION DENSITY (BRD)
MICRO FOCUSED (OR SINGLE POINT) RESISTIVITY
GAMMA RAY
CALIPER

The DR1 Sonde has been designed as a 'good hole' alternative to the DD1, combining an extremely high resolution Micro Resistivity device with an upgraded BRD measurement. Gamma Ray and Caliper logs are again included to provide further correlation, evaluation and tool alignment functions. The resulting log suite offers a higher resolution approach to basic logging in better quality open hole environments.

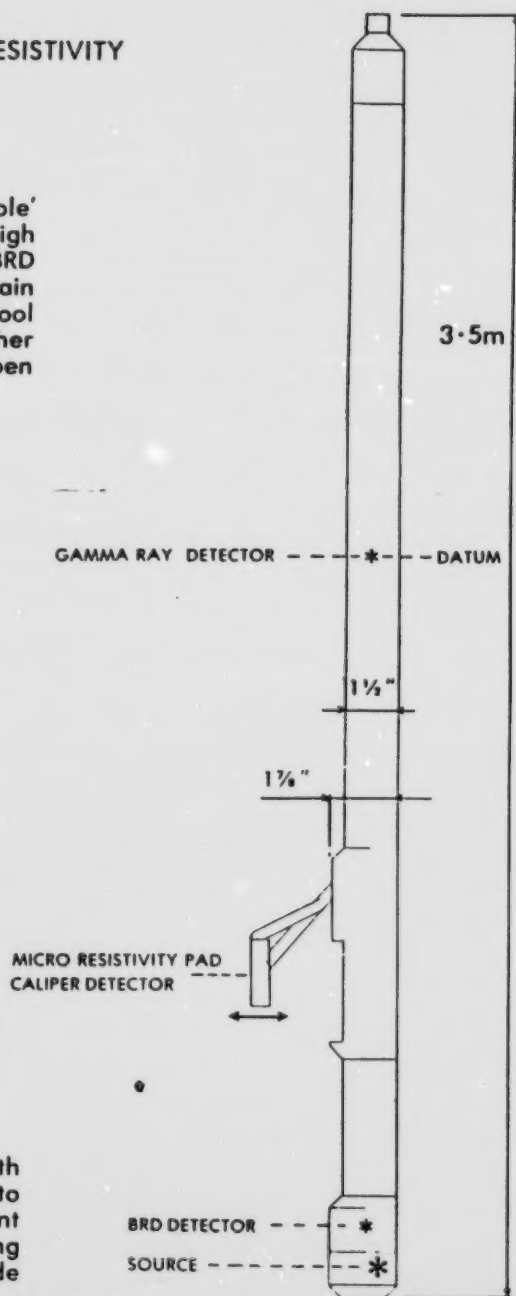
GENERAL SPECIFICATIONS:

Length — 3.50m (11.5')
Weight — 25kg (55lbs)
Diameter — 4.8cm (1 7/8") Max.
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm² (3000 psi)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole 6.5 to 30cm (2.5" to 12")
Logging Speed — standard logging: 9m/min (30' /min)
— detail logging: 2.25m/min (7.5' /min)
Logging Mode — sidewall, caliper eccentricised

Optimum logging requires open, fluid filled holes, with diameters less than 15cm (6"), although a modification to the resistivity arm can often provide Single Point Resistance logs in 'dry' holes. The adverse effects of caving can be more pronounced with this high resolution sonde than with the DD1 and care should be exercised.



TECHNICAL INFORMATION:

Gamma Ray — Measurement of naturally occurring radioactivity utilizes an uncollimated Sodium Iodide Crystal coupled to a Photo-multiplier Tube based amplifying system. Calibration, by active field jig, allows linear presentation in API units.

BR Density — Measurement of the level of scattered radiation uses a detecting system similar to that of the Gamma Ray but incorporating crystal shielding (sidewall collimation) and deadtime correcting circuitry. A two point calibration system utilizes large passive base facilities, translating responses into the field through more portable facilities to allow log presentation in gm/cc. With a source to detector spacing of 15cm (6") the BRD combines high resolution with quantitative measurement of bulk density for detailed formation evaluation. Optional Digital and Deconvolution filter facilities can provide further resolution enhancement down to 7cm (3").

Micro Resistivity — A sidewall, caliper pad mounted device provides, through a miniature laterolog arrangement, a shallow investigation log of electrical resistance. Kept in close contact with the borehole wall this pad, with a .5cm sense electrode, responds to formation resistivity changes with ultra high vertical resolution, enabling more precise boundary and parting definition to be achieved.

(A Single Point Scratcher device is available as an alternative means of obtaining an electric log and is often feasible in 'dry' boreholes).

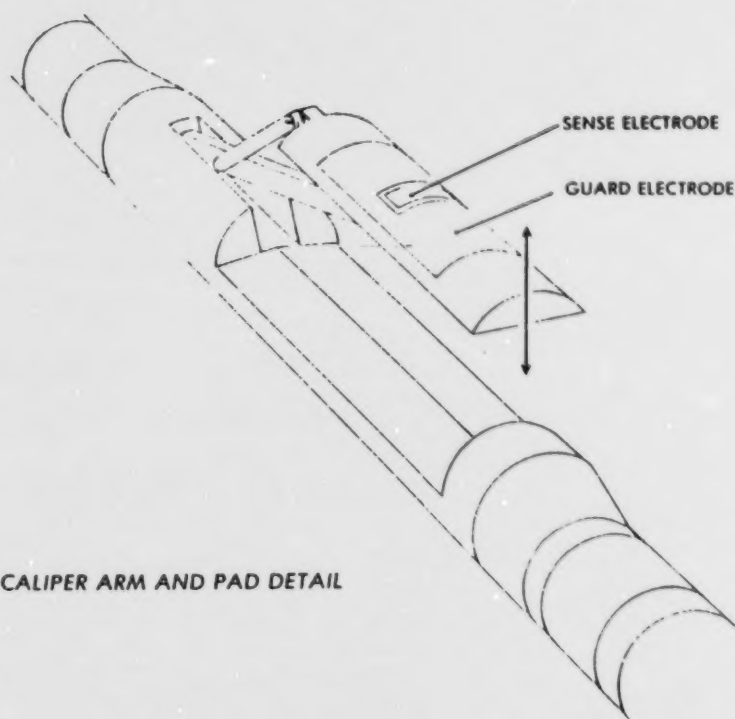


Fig. 1 — CALIPER ARM AND PAD DETAIL

Caliper — A single arm electro mechanical device carries the micro resistivity pad or single point electrode. It is held closed for entry into the borehole and activated during the logging run to provide caliper logging and to maintain sidewall configuration. Field calibration produces a linear measurement of hole diameter in inches or cm.

Hole diameter ranges:	Micro resistivity pad:	4.8cm to 30cm (1 7/8" to 12")
	Scratcher arm:	4.8cm to 35cm (1 7/8" to 13")

Source — A doubly encapsulated sealed source of Caesium 137 at an activity of 10 m Ci is mounted within a sidewall collimated holder and locked securely to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 8 mrem/hr.

PRESENTATION:

Logs are recorded in Metric or Imperial units and presented with full flexibility of scales and format. 'General' vertical scales range upwards from 100:1 whilst 'Detail' scale options, reserved for closer investigation of zones of interest, range down to 10:1. Some of the more usual presentations include:

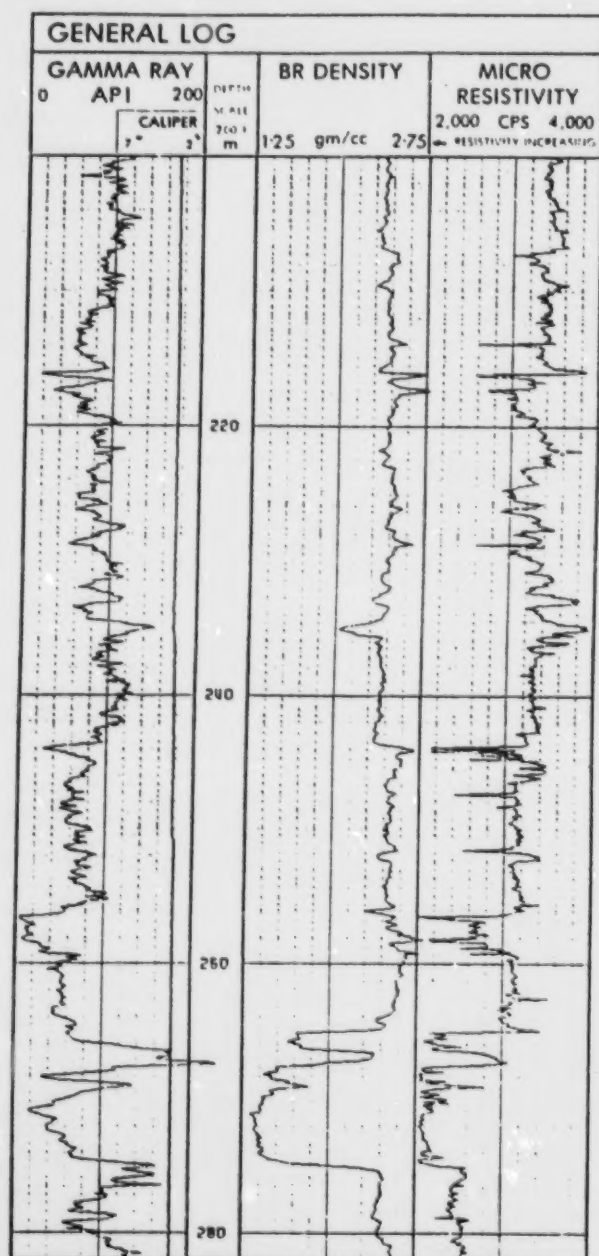
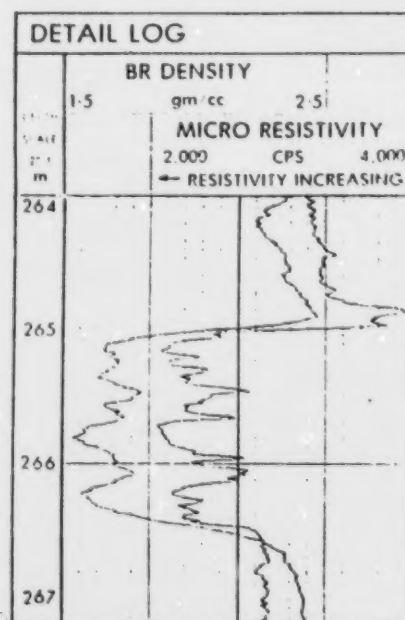


Fig. 2 — A GENERAL SCALE (200:1) PRESENTATION

Fig. 3

DETAIL SCALE LOGS (20:1), recorded through a coal seam to illustrate more clearly the high powers of vertical resolution of both the BRD and, to an even greater extent, the Micro Resistivity.



APPLICATION SUMMARY:

- GAMMA RAY** — Shale Content, Lithology Identification and Correlation.
- DENSITY: BRD** — Lithology Identification and Correlation plus quantitative evaluation of: Lithology, Porosity and other Formation properties and Strength Index (with Sonic) all at increased vertical resolution .
- MICRO RESISTIVITY** — Precise Boundary definition and indication of in seam shale and dirt partings.
- CALIPER** — Borehole diameter and caving profile (plus sidewall configuration and density correction).

The DRI suite provides improved qualitative and quantitative evaluations in good quality narrow diameter boreholes. It should be seen as a 'good caliper' alternative to the more universally applicable DD1 which, because of its deeper reading LS Density channel, can better cope with caving conditions.

REFERENCES:

Further information on many aspects of the DRI service may be found in the following BPB publications, available on request.

1. BPB Coal Interpretation Manual
2. The Radiation Density Log Applied to the Resolution of Thin Beds in Coal Measures
— J. R. Samworth
3. Slimline Dual Detector Density Logging, a Semi-Theoretical but Practical Approach to Correction and Compensation — J. R. Samworth

DD2 DUAL DENSITY, GAMMA RAY, SONDE.

(OR COAL TRI-SONDE)

MEASUREMENTS:

LONG SPACING DENSITY (LSD)
BED RESOLUTION DENSITY (BRD)
or HIGH RESOLUTION DENSITY (HRD)
GAMMA RAY

The DD2 Sonde has been designed as a specialist alternative to the more universal DD1, for use in more restricted diameters and/or for logging through casing or drill rods. It is a 3 channel device offering the option of either a 'BRD' or an 'HRD' measurement as the higher resolution density log.

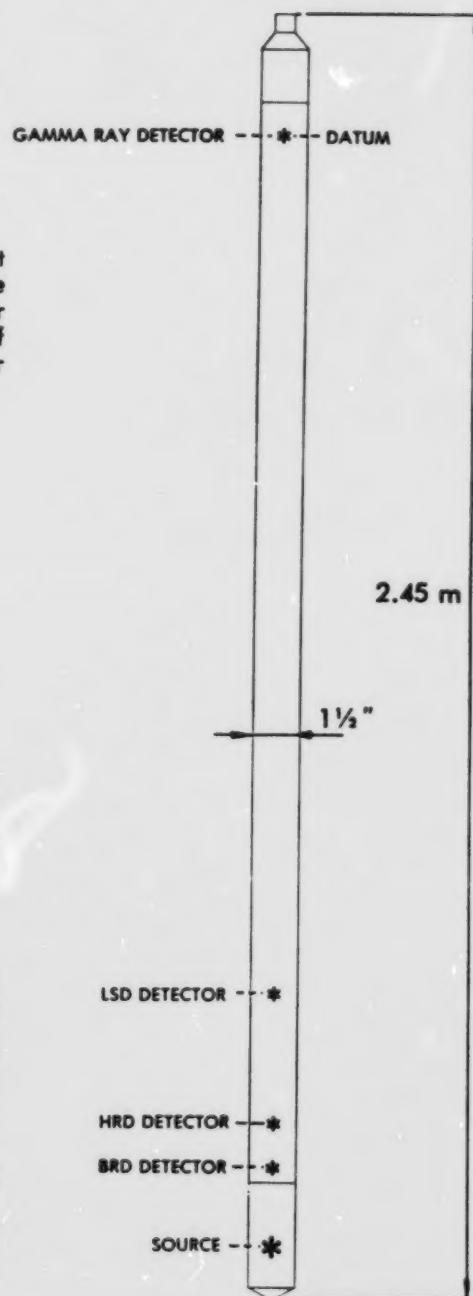
GENERAL SPECIFICATIONS:

Length — 2.45 m (8')
Weight — 14 kg (30 lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000 m (6500')
Hole Diameter — open hole: 6 to 20 cm (2½" to 8")
— casing or rods: 5 to 20 cm (2" to 8")
Logging Speed — standard logging: 9 m/min (30' /m)
— detail logging: 2.25 m/min (7.5' /m)
Logging Mode — free running

The DD2 Sonde can provide good basic logging in difficult borehole conditions which may preclude the use of the DD1 sonde. Environments may include dry or fluid filled holes and logging may proceed in open hole, through casing (conventional or plastic) or through the drill rods, as formation stability problems dictate.



TECHNICAL INFORMATION:

GAMMA RAY — Measurement of naturally occurring radioactivity utilizes an identical system to that incorporated in the DD1 Sonde.

DENSITY — The principle of operation remains as described in the DD1 leaflet, although the overall systems do differ in some significant ways, specifically:

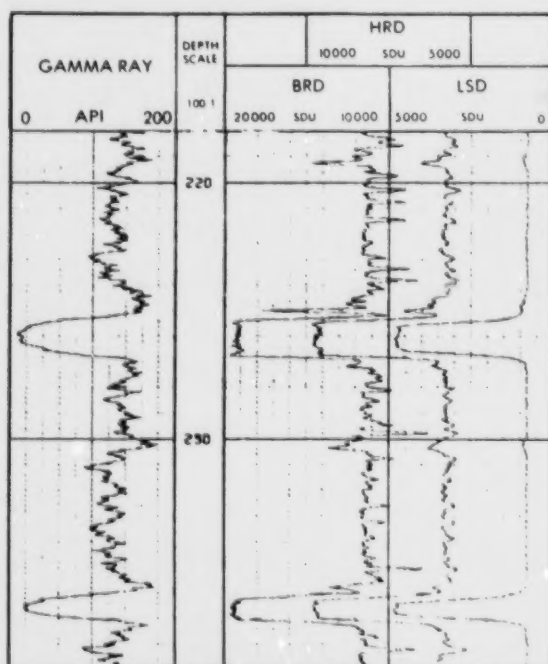
- both density channels operate without collimation of either the source or detectors, i.e. measurements utilize a full 360° window around the borehole wall,
- the sonde operates in a 'free running' mode, as opposed to the caliper controlled 'sidewall' configuration of the DD1.

LSD — A source to detector spacing of 48 cm (19") is maintained.

BRD (or HRD) — The standard mode of operation offers a 15 cm (6") spacing BRD log as the higher resolution density channel, although the option exists for this to be modified to a 24 cm (9.5") HRD measurement as required.

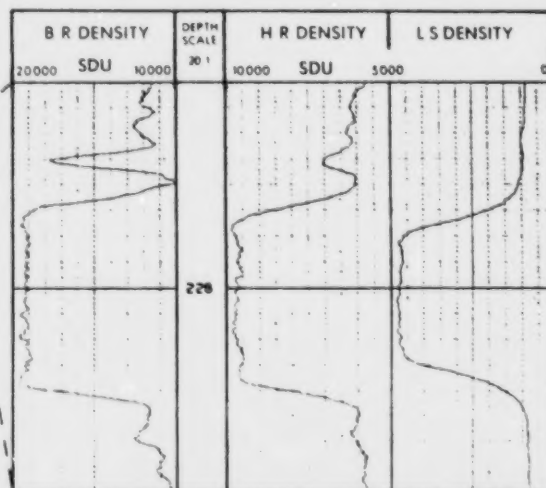
SOURCE — A doubly encapsulated sealed source of Caesium 137 at an activity of 50 mCi, is mounted within a holder securely locked to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 7 mrem/hr.

PRESENTATION:



General Scale Lithology Logging

Metric or Imperial scale logs may be presented on any API based format. 'General' scales range from 100:1 upward whilst 'Detail' scales, reserved for closer investigation of zones of interest, are available down to 10:1.



Detail Scale Seam Evaluation

APPLICATION SUMMARY:

The DD2 provides a basic single run Gamma/Density evaluation package, primarily for application where borehole conditions preclude use of the DD1.

- GAMMA RAY** — Shale content, Lithology identification and Correlation
- DENSITY : LSD** — Lithology identification and Correlation, Porosity indicator
- BRD (or HRD)** — More precise boundary definition and seam thickness evaluation

REFERENCES:

Further information may be found in: The DD1 Sonde — Subsurface leaflet No. 1

NO1 NEUTRON SONDE

MEASUREMENTS:

LONG SPACING NEUTRON (LSN)
or SHORT SPACING NEUTRON (SSN)

The NO1 single function sonde provides Neutron log options in all ranges of borehole conditions generally associated with slimhole drilling. Long Spacing based porosity logging is standard although a Short Spacing option can be made available for higher resolution work in better quality boreholes.

GENERAL SPECIFICATIONS:

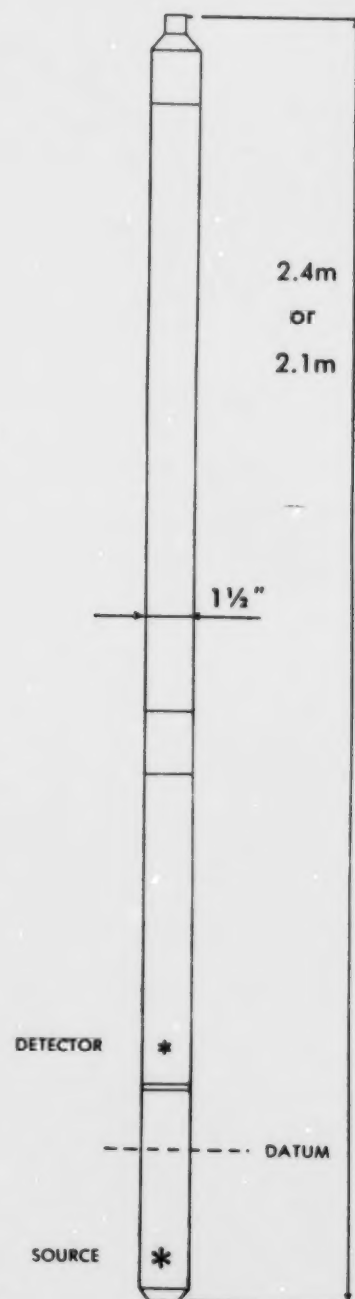
Length	— Long spacing mode 2.41m (8')
	— Short spacing mode 2.13m (7')
Weight	— 11Kg (24lbs)
Diameter	— 3.8cm (1.5")
Temperature	— up to 70°C (158°F)
Pressure	— up to 210kg/cm ² (3000) psi

OPERATING CONDITIONS:

Hole Depth	— to a max. of approx. 2000m (6500')
Hole Diameters	— open hole: 6.0 to 30cm (2.5 to 12")
	— casing or rods: 5.0 to 30cm (2.0 to 12")
Logging Speeds	— standardly 9m/min (30'/min)
	— detail logging 2.25m/min (7.5'/min)
Logging Mode	— free running

Porosity calibration is based on the Long Spacing option and requires that logging be performed in open, fluid filled boreholes; although valuable qualitative logs may also be obtained from Long or Short Spacing logs in dry holes and through casing or drill rods.

Although less effected by borehole rugosity than most other slimhole tools, the Neutron log will, even in its long spacing form, be adversely affected by excessive caving.



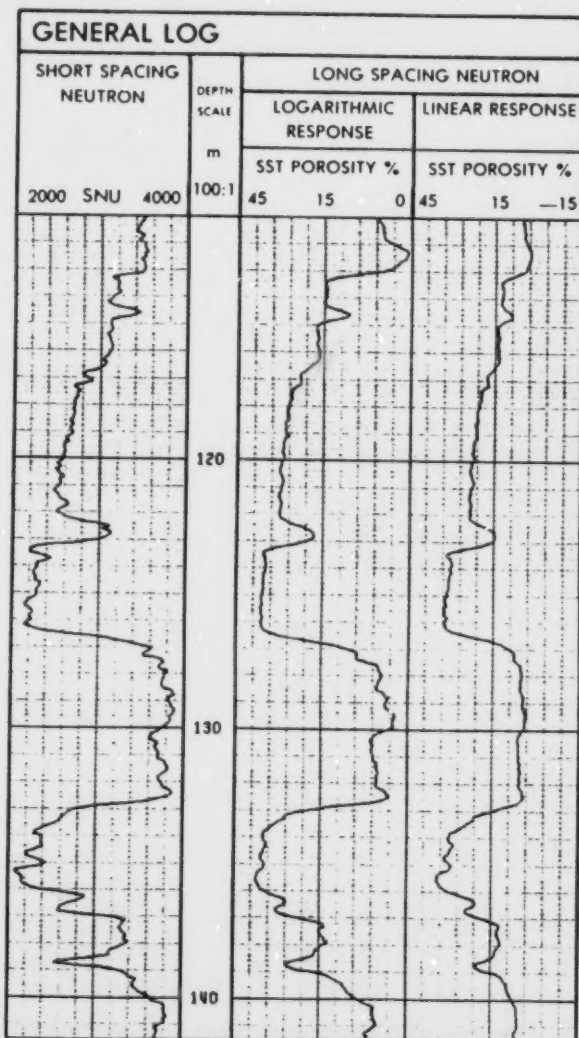
TECHNICAL INFORMATION:

The Neutron log is essentially a measurement of the ability of the formation to thermalise (slow down) high energy neutrons as emitted from the logging source. Being a function of the presence of lighter elements (primarily hydrogen) this log, after correction for borehole effects, may be presented as an Index of Hydrogen and/or in turn as a measurement of Formation Porosity.

High energy Neutrons are emitted with a 360° window from the logging source attached respectively 44cm (Long Spacing) or 25cm (Short Spacing alternative) beneath the uncollimated Helium₃ detector tube. Calibration utilises portable passive jigs to allow log presentation in porosity units.

SOURCE — a double encapsulated sealed source of Americium 241/Beryllium at an activity of One Curie is mounted in a stainless steel holder and locked securely to the sonde during logging operations. The source holder is transported in a purpose designed shield with a maximum surface radiation level of 2 mR/hr (gamma) and 6 mR/hr (Neutron).

PRESENTATION:



The Long Spacing Neutron porosity log is standardly presented with a logarithmic response emphasising the Lower porosity range, with a linear response option available after further processing. Both LSN and SSN logs are available with a full flexibility of scales and formats on the API grid.

APPLICATIONS:

LONG SPACING NEUTRON — Lithology identification and correlation in the full range of open, cased (or thr' drill rods), fluid filled and dry boreholes; with quantitative measurement of porosity allowing formation evaluation in open fluid filled holes.

SHORT SPACING NEUTRON — A 'good hole' alternative to the LSN offering higher vertical resolution for more detailed evaluation.

REFERENCE:

BPB Coal Interpretation Manual.

V01, V02

VERTICALITY SONDES

MEASUREMENTS:

HOLE TILT
AZIMUTH OF HOLE TILT
TRUE VERTICAL DEPTH
TRUE HOLE POSITION

The Verticality Sonde provides a full and continuous slimhole directional survey, primarily in open hole environments. Tilt and Azimuth data are recorded throughout the logging run with further processing adding True Depth and Position with respect to the upper reference point (surface or casing shoe). Additional options offer a more comprehensive evaluation and graphical presentation of all output.

Two versions are offered: V01 being the standard with V02 offering measurement over a larger range of hole tilt angles.

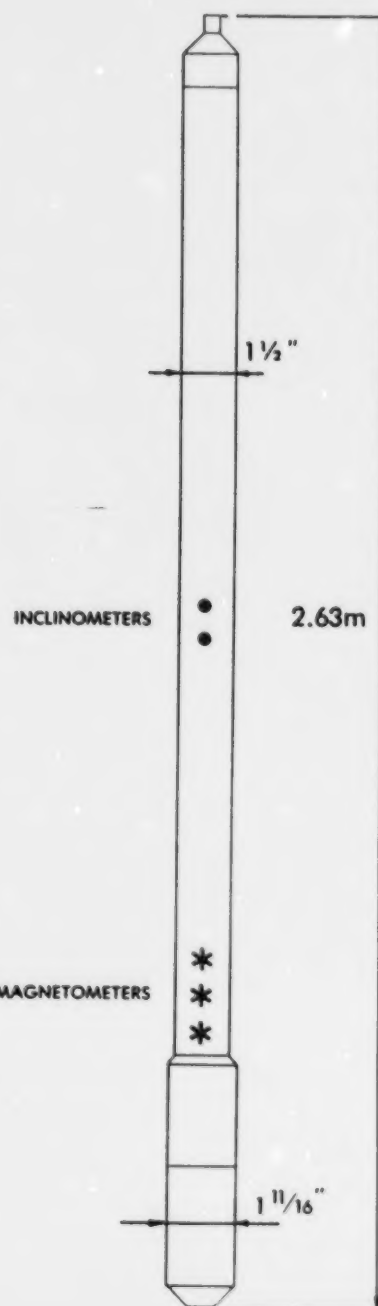
GENERAL SPECIFICATIONS:

Length — 2.63m (8.6')
Weight — 10kg (22lbs)
Diameter — 4.2cm (1.7") max
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

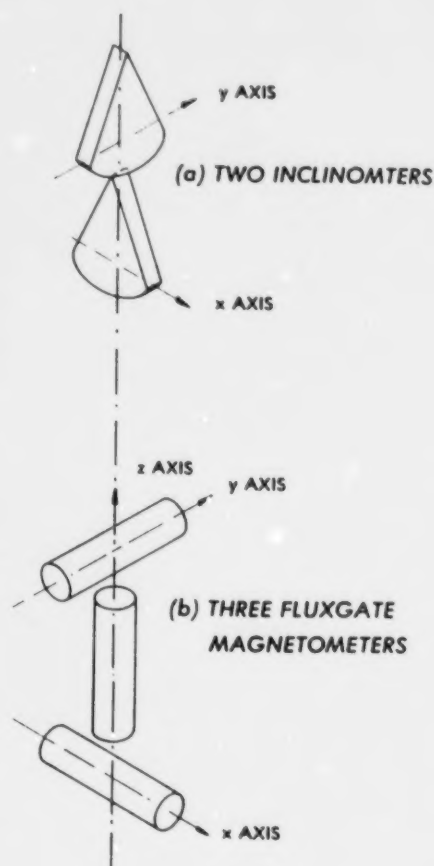
Hole Depth — to a max of approx. 2000m (6500')
Hole Diameter — open hole: 6.5 to 30cm (2.5" to 12")
Logging Speed — standardly: 9m/min (30'/min)
Logging Mode — free running

The Verticality Sonde functions equally well in both fluid filled and dry boreholes. It is primarily an open hole survey tool, the use of magnetometer transducers prevents the acquisition of azimuth data (and hence calculation of hole position) through conventional casing or drill rods. This survey is largely unaffected by even quite serious caving in slimhole environments.



TECHNICAL INFORMATION:

Five transducers in fixed alignment on the three axes of the sonde enable continuous monitoring of its orientation. The diameter constraints associated with slimline tool design call for a solid state approach to transducer design, in contrast to the much larger electro-mechanical devices incorporated in conventional oilfield systems.



Two inclinometers define the sonde's minor (x and y) axes (fig. 1a) and provide measurement of both the borehole tilt with respect to vertical and of the direction of tilt with respect to a 'reference'.

Three fluxgate magnetometers mounted on the sonde's (x, y and z) axes (fig. 1b) add a knowledge of the rotational orientation of the sonde and, in conjunction with the tilt measurement, provide measurement of the azimuth of the 'reference' with respect to Magnetic North.

Hence: Tilt w.r.t. Vertical and Azimuth of Tilt w.r.t. Mag.N (or True N with the input of the local angle of declination)

Fig. 1 Transducer Schematic.

Calibration is performed regularly in a mechanical jig facility backed up with simple field checks made directly before and after the logging of each hole.

The outputs of all five transducers are transmitted for continuous surface recording throughout the logging run, during which they are translated into spot readings of Tilt and Azimuth as a function of log depth.

Various processing options are available upon completion of the logging run to provide True Vertical Depth and True Hole Position as functions of log depth and w.r.t. surface or casing shoe.

Each sonde is standardly set for:

V01 — range 0 to 20°, the standard option for nominally vertical holes with accuracies of $\pm \frac{1}{2}^\circ$ on inclination and $\pm 10^\circ$ on azimuth,

V02 — range 0 to 40°, with accuracies of $\pm 2^\circ$ on inclination and $\pm 10^\circ$ on azimuth, although in certain circumstances either sonde may be retuned to provide increased accuracy over a decreased range of inclination.

PRESENTATION:

Two forms of output are available, both of which can be set for either metric or imperial units.

(A) VIA LOG PROCESSOR. Hole survey result listings are presented automatically on a fixed 10m (or 50 ft) log depth incremental basis.

DEPTH = 1600.00
TILT = 2.61 DG
BEARING = 198.92 DG
DEPTH = 1650.00
TILT = 2.35 DG
BEARING = 207.75 DG
DEPTH = 1700.00
TILT = 2.41 DG
BEARING = 202.43 DG
DEPTH = 1750.00
TILT = 2.46 DG
BEARING = 199.33 DG
DEPTH = 1800.00
TILT = 2.36 DG
BEARING = 193.43 DG
DEPTH = 1850.00
TILT = 2.49 DG
BEARING = 201.56 DG
DEPTH = 1900.00
TILT = 2.78 DG
BEARING = 199.14 DG

Fig. 2a. Listing created during the logging run, of Tilt and Azimuth w.r.t. Magnetic or True North (Bearing) as a function of log depth.

LOG DEPTH = 1600.00
TRUE DEPTH = 1600.00
TILT = 2.61 DG
BEARING = 198.92 DG
NORTHING = 1600.00
EASTING = 0.00
LOG DEPTH = 1650.00
TRUE DEPTH = 1650.00
TILT = 2.35 DG
BEARING = 207.75 DG
NORTHING = 1650.00
EASTING = 0.00
LOG DEPTH = 1700.00
TRUE DEPTH = 1700.00
TILT = 2.41 DG
BEARING = 202.43 DG
NORTHING = 1700.00
EASTING = 0.00
LOG DEPTH = 1750.00
TRUE DEPTH = 1750.00
TILT = 2.46 DG
BEARING = 199.33 DG
NORTHING = 1750.00
EASTING = 0.00
LOG DEPTH = 1800.00
TRUE DEPTH = 1800.00
TILT = 2.36 DG
BEARING = 193.43 DG
NORTHING = 1800.00
EASTING = 0.00
LOG DEPTH = 1850.00
TRUE DEPTH = 1850.00
TILT = 2.49 DG
BEARING = 201.56 DG
NORTHING = 1850.00
EASTING = 0.00
LOG DEPTH = 1900.00
TRUE DEPTH = 1900.00
TILT = 2.78 DG
BEARING = 199.14 DG
NORTHING = 1900.00
EASTING = 0.00

Fig. 2b. Listing created on completion of the logging run adds true depth and hole position w.r.t. the upper reference point.

(B) VIA COMPUTER GRAPHICS UNIT. Provides full graphical analysis of hole survey data as well as more comprehensive listings of hole position in both Axial and Polar co-ordinates. Other advantages of this approach include:

- error analysis on hole position
- presentation scale flexibility
- cross sections selectable at any specified depth
- facility to join data from separate logging runs

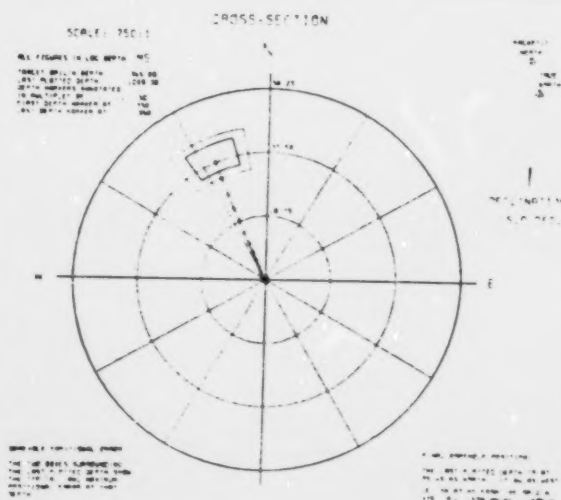


Fig. 3a Borehole Cross Section, Plan View of the Full Logged Interval.

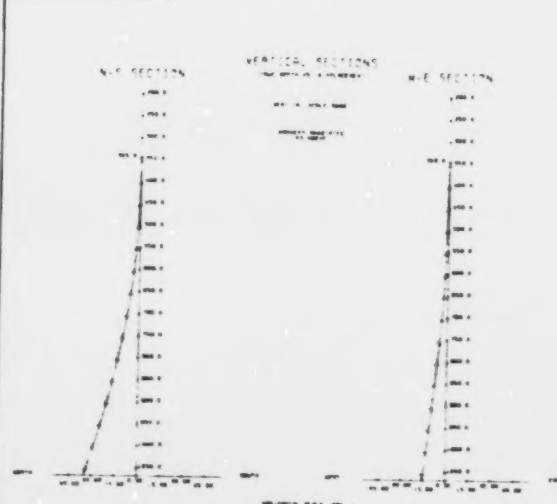


Fig. 3b Borehole Vertical Sections, Side View of the Full Logged Intervals in N-S and W-E vertical planes.

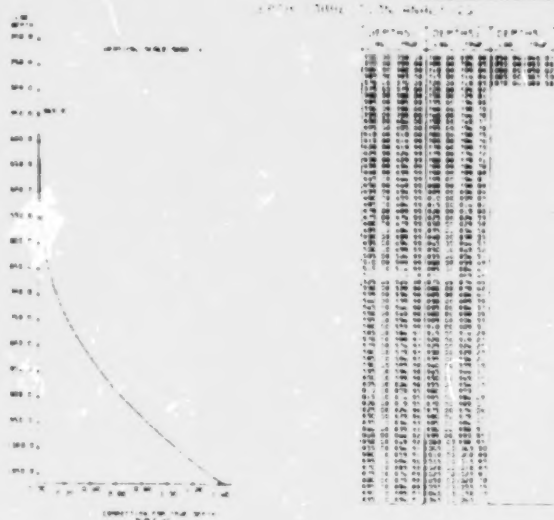


Fig. 3c Depth Correction Analysis in graphical and tabulated form.

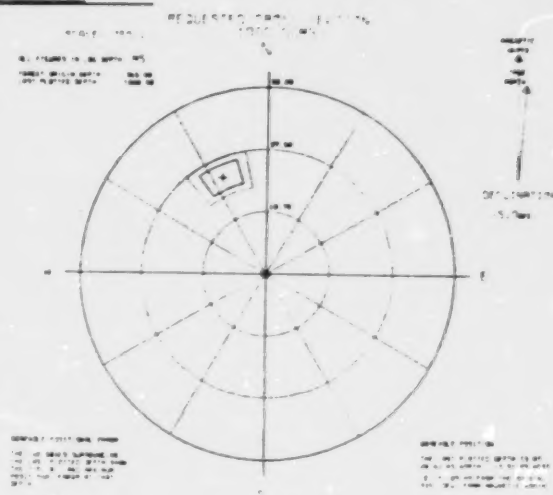


Fig. 3d Requested Cross Section at any specified depth.

Verticality Data Listing										Date processed: 26-APR-83					
DEPTHS		All co-ordinates with respect to Magnetic North						POLAR ERROR CO-ORDINATES (maximum & typical)							
log	true	BOREHOLE tilt	AZI	AXIAL North	CO-ORDS. East	POLAR brng radius	POLAR brng radius	CO-ORDINATES brng radius	CO-ORDINATES brng radius	CO-ORDINATES brng radius	CO-ORDINATES brng radius	CO-ORDINATES brng radius	CO-ORDINATES brng radius		
350.00	350.00	0.7	293.	0.03	-0.04	300.	0.05	300.	0.09	296.	0.01	300.	0.08	299.	0.02
355.00	355.00	0.7	293.	0.05	-0.10	297.	0.11	298.	0.20	295.	0.02	298.	0.17	297.	0.05
360.00	360.00	0.6	290.	0.08	-0.15	297.	0.17	297.	0.30	296.	0.04	297.	0.25	296.	0.08
365.00	365.00	0.7	300.	0.10	-0.20	296.	0.22	297.	0.40	296.	0.05	297.	0.34	296.	0.11
370.00	370.00	0.8	293.	0.12	-0.25	296.	0.28	296.	0.50	295.	0.07	296.	0.43	296.	0.14
375.00	375.00	0.7	292.	0.15	-0.31	295.	0.35	295.	0.61	294.	0.09	295.	0.52	295.	0.17
380.00	380.00	0.6	297.	0.17	-0.37	295.	0.41	295.	0.71	294.	0.11	295.	0.61	295.	0.21
385.00	385.00	0.6	306.	0.20	-0.40	296.	0.46	296.	0.61	295.	0.12	296.	0.70	295.	0.23
390.00	390.00	0.9	304.	0.23	-0.46	296.	0.51	296.	0.91	295.	0.12	296.	0.77	296.	0.25
395.00	395.00	0.7	302.	0.26	-0.52	297.	0.50	297.	1.01	296.	0.14	297.	0.87	297.	0.29
400.00	400.00	0.7	300.	0.30	-0.57	298.	0.64	298.	1.12	298.	0.17	298.	0.96	298.	0.33

Fig. 3e Full Data Listings

APPLICATION SUMMARY:

Hole surveying becomes particularly important in mine or production planning, where it is essential to understand the actual performance of any borehole as it relates to the real positions and true depths of intersection with specific horizons. The importance of such information increases with depth as borehole performance assumptions can become significantly and increasingly inaccurate.

REFERENCES:

NB — The Verticality Sonde can be run alone or in conjunction with an attachable microresistivity/caliper section to create the Dipmeter Sonde. Here Verticality data continues to provide this full hole survey as well as enabling the measured strata dip to be referenced to the horizontal and it's direction orientated w.r.t. Magnetic or True North (see Leaflet Subsurface No. 9).

Further details of the Verticality service may be found in the following BPB publications available on request:

1. BPB Coal Interpretation Manual
2. Slimhole Dipmeter — R W Wroot

DV1, DV2

DIPMETER SONDES

(INCLUDES THE VERTICALITY SONDE)

MEASUREMENTS:

FORMATION DIP — MAGNITUDE
— AZIMUTH

HOLE VERTICALITY — output as per
Verticality Sonde,
see leaflet:
Subsurface No. 8.

The Dipmeter Sonde is a 3 arm device designed to measure formation dip, and provide a complete hole survey, in nominally vertical or slightly deviated slimline boreholes. Two versions are offered: DV1 being the standard with DV2 a slightly larger version providing increased sidewall thrust for use at higher degrees of borehole tilt, at larger diameters or in more rugous boreholes.

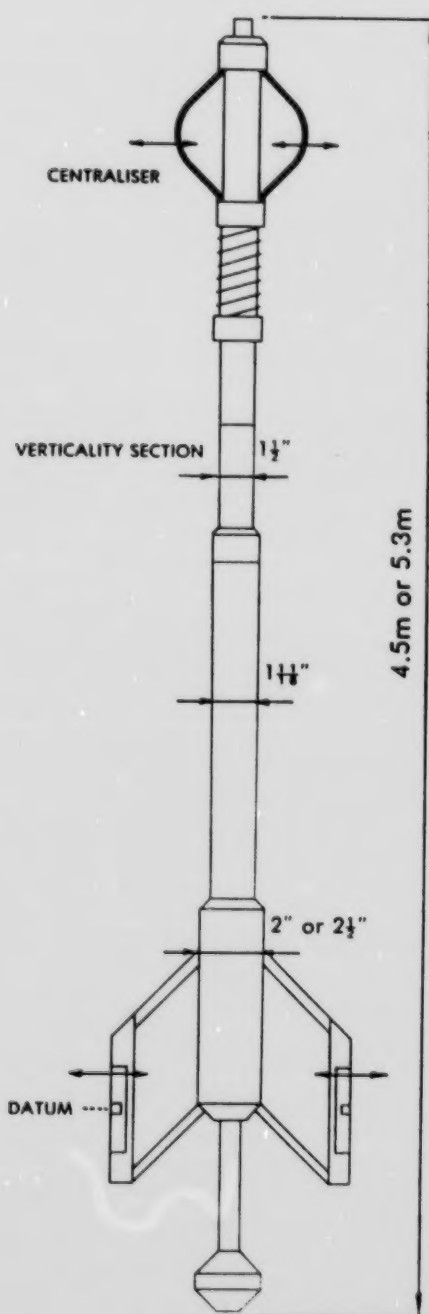
GENERAL SPECIFICATIONS:

	DV1	DV2
Length	— 4.5m (14.8')	5.3m (17.4')
Weight	— 24.5kg (54lbs)	36.0kg (79lbs)
Diameter	— 5.1cm (2")	6.4cm (2½")
Temperature	— up to 70°C (158°F)	
Pressure	— up to 210kg/cm ² (3000 psi)	

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole, DV1: 7.5 to 20cm (3 to 8")
DV2: 10.0 to 25cm (4 to 10")
Logging Speed — 4m/min (13' /min)
Logging Mode — centralized by the 3 caliper arms, aided in larger diameters by a passive guide system mounted on the upper section.

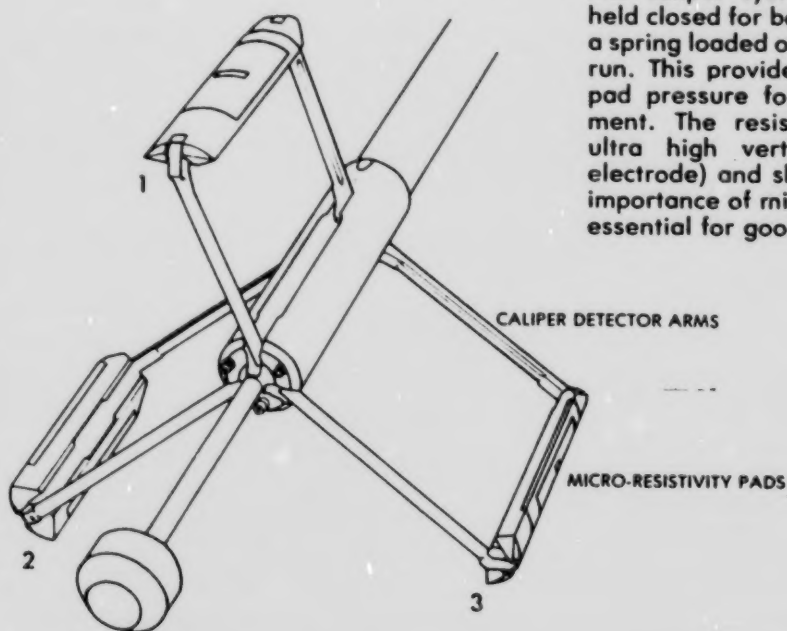
Formation dip can only be measured in open, fluid filled boreholes. Optimum results will be seen in small diameter boreholes (6" or less), with good caliper and with mud resistivities in the approximate range of 1 to 10 ohm metres. The DV1 Sonde will operate up to borehole tilts of



TECHNICAL INFORMATION:

The Dipmeter Sonde is designed to enable identification and measurement of offsets in the depths of features as seen by three detector pads, spaced around the borehole wall with 120° angular separation. Addition of pad direction and hole caliper data enables translation of these offsets into a measurement of 'Apparent' dip, i.e. dip with respect to the borehole. Conversion to 'True' dip may then be achieved by correcting for the effects of hole tilt, allowing presentation of Dip Magnitude w.r.t. the Horizontal and Dip Direction w.r.t. North.

The three circumferential measurements are made by caliper mounted microfocussed resistivity pads, assembled beneath an orientation sub section — the Verticality Sonde when run alone as a hole survey device. Sonde assembly aligns pad 1 into the x-axis of the verticality section (see leaflet No. 8) to allow orientation of the dip plane and presentation of True Dip, irrespective of hole tilt or sonde rotation, see ref. 2.



The caliper system is motor controlled, being held closed for borehole entry and activated into a spring loaded open position prior to the logging run. This provides both borehole diameter and pad pressure for sidewall resistivity measurement. The resistivity logs are recorded with ultra high vertical resolution (0.5cm sense electrode) and shallow investigation (hence the importance of minimising borehole caving), both essential for good dip measurements.

Fig. 1 Pad and Arm Detail

In operation the Dipmeter Sonde transmits 9 channels of data for surface recording on magnetic tape as continuous depth based logs.

In summary:

3 X microfocussed resistivities	} Verticality Sonde	} Dipmeter Sonde
1 X caliper		
2 X inclinometers		
3 X magnetometers		

Field presentation consists primarily of displaying the resistivity logs and monitoring all other data channels, to ensure that adequate quality data is available to the subsequent interpretation system. The quantity of data involved and the nature of the processing inevitably defines the need for a computer based approach to interpretation and result presentation.

PRESENTATION:

Dipmeter logging offers all of the hole survey analysis options described in leaflet No. 8 in addition to the evaluation of formation dip illustrated below. Both Metric and Imperial data can be processed, with results available on a full variety of vertical scales.

Fig. 2 is an example of the final 'tadpole plot' output of the computer package, implementation of which requires the selection of certain interpretation parameters. The following notes summarize the process and describe the illustrated output, although comprehensive discussions are a little beyond the scope of this 'sonde' leaflet.

At the heart of the interpretation is computer matching of sections of the three resistivity curves, to determine offsets between pads 1-2 and 1-3. Such 'correlations' are graded up to a maximum value of 1.0, this grading remaining as a measure of confidence in the resulting calculation of dip at that depth.

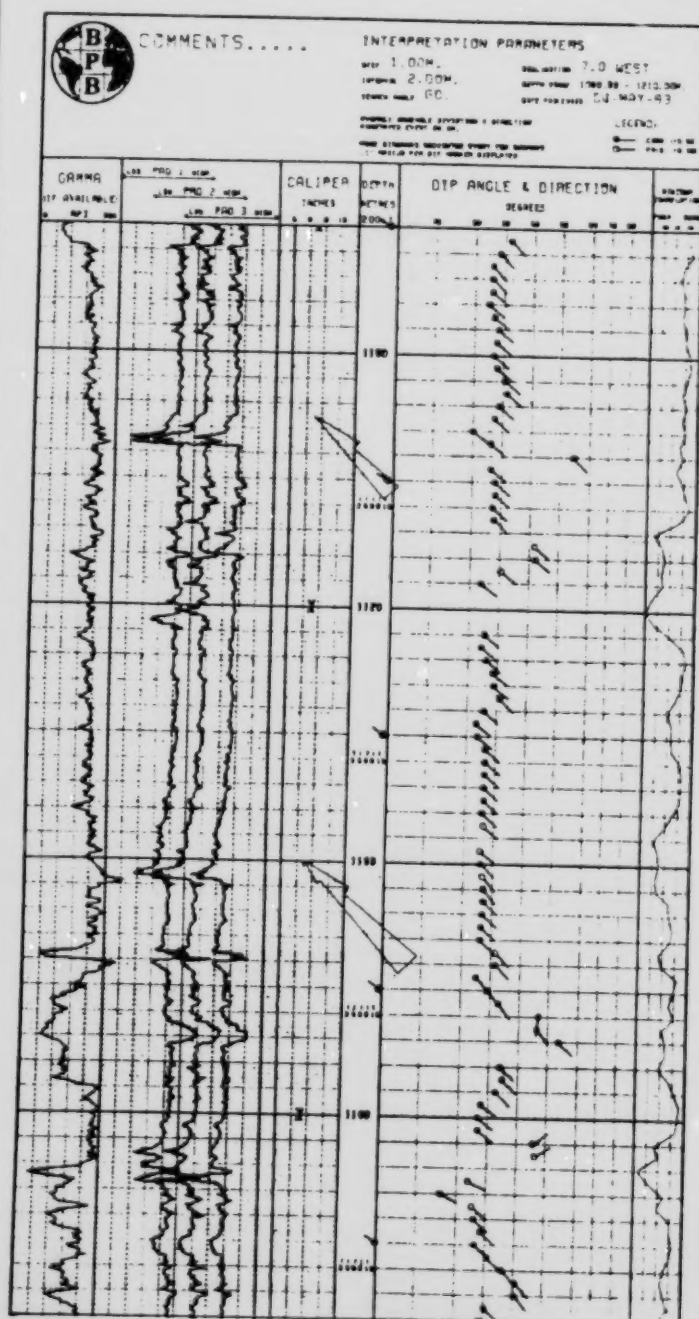


Fig. 2 Dipmeter Interpretation, Standard Output

TRUE DIP MAGNITUDE

— is indicated w.r.t. Horizontal by the position of the tadpole body.

TRUE DIP DIRECTION

— is indicated by the direction of the tail of the tadpole, True North being represented by a vertically upward pointing tail.

BOREHOLE TILT

— both tilt and its azimuth are indicated by slightly larger tadpoles, presenting averaged values periodically in the depth margin.

Step, Interval, Search Angle and Declination Angle are all selectable options defining the way in which interpretation is to proceed:

STEP

— is the distance between successive correlation depths.

INTERVAL

— is the length of Pad 1 curve used in each correlation.

SEARCH ANGLE

— is the maximum formation dip for which the program is allowed to search.

DECLINATION ANGLE

— is the local relationship between Magnetic and True North, input to allow presentation of directions w.r.t. True North.

A Gamma Ray log is plotted with the three resistivity curves to assist formation identification and correlation.

The Caliper log is presented as a monitor of hole condition.

'Rose Diagrams' or dip azimuth frequency plots are presented on a periodic basis through sections of the borehole as arrowed.

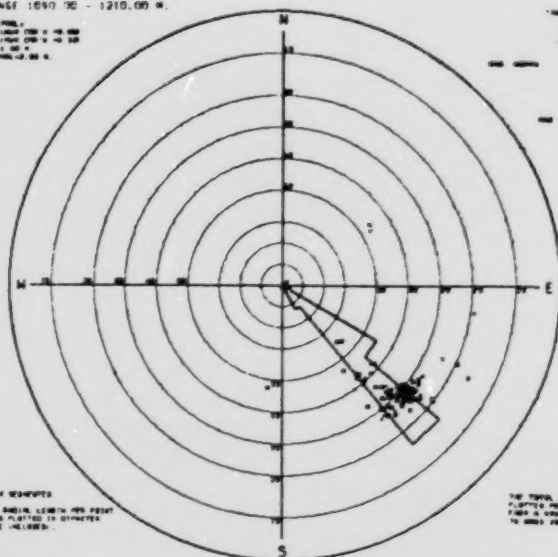
Minimum correlations are plotted to illustrate the value of the poorest of the two pad curve correlations (1-2 and 1-3) made for each dip calculation. The minimum correlation value also defines the presentation of dip according to the criteria listed in the legend:

Solid tadpoles represent 'good' or high confidence dips, and open tadpoles represent 'fair' or medium confidence dips, with 'poor' or low confidence dips left out of the final plot.

This criteria is determined during a preliminary phase (output not illustrated), during which all correlations are presented irre-

DEPTH RANGE: 1090.00 - 1210.00 M.

QUALITY CONTROL:
 0 2000 HOURS 100% 0 10.00
 1 1000 HOURS 100% 0 10.00
 2 000 HOURS 100% 0 10.00
 3 000 HOURS 100% 0 10.00



NOTE: DIPS ARE MEASURED
 FROM 10
 0.000 TO 10.000 LENGTH PER POINT
 POINTS ARE PLotted IN ORDER
 QUALITY ARE INCLUDED

THE TOTAL NUMBER OF
 POINTS MEASURED WAS 107
 FROM A DIPS OF 110
 TO 1000 TO 10.00

Fig. 3

As an optional extra presentation this Dipmeter Point Distribution Analysis illustrates the frequency distribution of both dip magnitude and azimuth over any specified depth interval(s).

Magnetic declination 7.88 degrees West of North
 Correlation step: 0.00 metres, Interval: 2.00 metres Search angle 50. degrees

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 PAGE 1

DEPTH	CAL.	BOREHOLE	FORMATION	MIN.	DEPTH	CAL.	BOREHOLE	FORMATION	MIN.	DEPTH	CAL.	BOREHOLE	FORMATION	MIN.						
metres	ins.	TIPT	AZI	DIP	metres	ins.	TIPT	AZI	DIP	metres	ins.	TIPT	AZI	DIP						
1091.00	3.9	9.8	303.	32.4	130.	0.78	1092.00	3.9	9.8	303.	29.4	130.	0.85	1093.00	3.9	9.8	303.	26.8	140.	0.67
1094.00	3.9	9.8	303.	26.5	134.	0.63	1095.00	3.9	9.8	303.	26.0	132.	0.69	1096.00	3.9	9.9	303.	25.5	132.	0.70
1097.00	3.9	9.9	303.	27.5	130.	0.64	1098.00	4.0	9.9	303.	29.1	128.	0.73	1099.00	3.9	9.9	303.	28.6	129.	0.74
1100.00	3.9	9.9	303.	27.5	130.	0.83	1101.00	3.9	9.9	303.	28.0	129.	0.86	1102.00	3.9	9.9	303.	30.0	130.	0.76
1103.00	3.9	9.9	303.	31.5	131.	0.72	1104.00	3.9	9.9	303.	29.9	131.	0.70	1105.00	3.9	10.0	304.	28.3	131.	0.69
1106.00	3.9	10.0	304.	20.1	127.	0.77	1107.00	4.0	10.0	304.	27.1	131.	0.67	1108.00	4.0	10.1	304.	55.2	135.	0.71
1109.00	3.9	10.1	304.	27.2	130.	0.59	1110.00	3.9	10.1	304.	28.7	132.	0.71	1111.00	3.9	10.2	304.	28.9	131.	0.70
1112.00	3.9	10.2	304.	28.0	131.	0.87	1113.00	3.9	10.2	304.	28.7	135.	0.66	1114.00	3.9	10.2	304.	30.1	130.	0.77
1115.00	4.0	10.3	305.	41.9	129.	0.35	1116.00	3.9	10.3	305.	42.3	131.	0.40	1117.00	3.9	10.3	305.	30.6	129.	0.33
1118.00	4.0	10.4	305.	24.3	120.	0.35	1119.00	4.0	10.4	305.	23.1	125.	0.15	1120.00	4.0	10.4	305.	31.9	303.	0.91
1121.00	4.0	10.4	305.	26.8	130.	0.20	1122.00	4.0	10.4	305.	26.1	1270.	0.53	1123.00	4.0	10.4	305.	25.1	131.	0.79
1124.00	4.0	10.4	305.	27.1	131.	0.84	1125.00	4.0	10.4	305.	29.5	129.	0.77	1126.00	4.0	10.5	305.	29.9	129.	0.76
1127.00	4.0	10.5	305.	31.2	136.	0.65	1128.00	4.0	10.5	305.	26.4	130.	0.50	1129.00	4.0	10.5	305.	23.6	129.	0.50
1130.00	4.0	10.5	305.	24.2	130.	0.58	1131.00	4.0	10.6	306.	27.4	131.	0.59	1132.00	4.0	10.6	306.	27.4	130.	0.77
1133.00	4.0	10.6	306.	27.4	130.	0.80	1134.00	4.0	10.6	306.	27.0	130.	0.79	1135.00	4.0	10.7	306.	27.2	132.	0.70
1136.00	4.0	10.7	306.	26.7	132.	0.62	1137.00	4.0	10.7	306.	27.1	132.	0.48	1138.00	4.0	10.7	306.	65.4	138.	0.20
1139.00	4.0	10.7	306.	26.2	129.	0.37	1140.00	4.0	10.7	307.	26.5	137.	0.49	1141.00	4.0	10.7	307.	27.3	143.	0.32

Fig. 4

Comprehensive listings presented as part of the standard dipmeter interpretation package.

APPLICATIONS:

The Dipmeter provides structural information and enables apparent formation thicknesses to be corrected for the combined effects of formation dip and hole tilt.

Parameter selection, primarily of the interval, is all important and should be specified in accordance with the required application. Generally speaking long intervals will reveal structural dips whereas shorter intervals will be more suitable for the determination of finer details of dip associated with sedimentation studies. 1 to 2m intervals offer a good compromise and are usually used in the first instance.

Inspection of overall trends may often reveal faulting and other important geological features.

REFERENCES:

Further information on the Slimline Dipmeter service may be found in the following BPB publications, available on request:

1. BPB Coal Interpretation Manual¹.
2. Slim Hole Dipmeter — R W Wroot.

TT1 TEMPERATURE SONDE

MEASUREMENTS:

ABSOLUTE TEMPERATURE
TEMPERATURE DIFFERENCE
TEMPERATURE DIFFERENTIAL

The TT1 Sonde provides an absolute temperature profile as a function of borehole depth, highlighting local anomalies through closer inspection of the temperature changes seen. For optimum results the borehole should be allowed to stand for 12-24 hours prior to temperature logging.

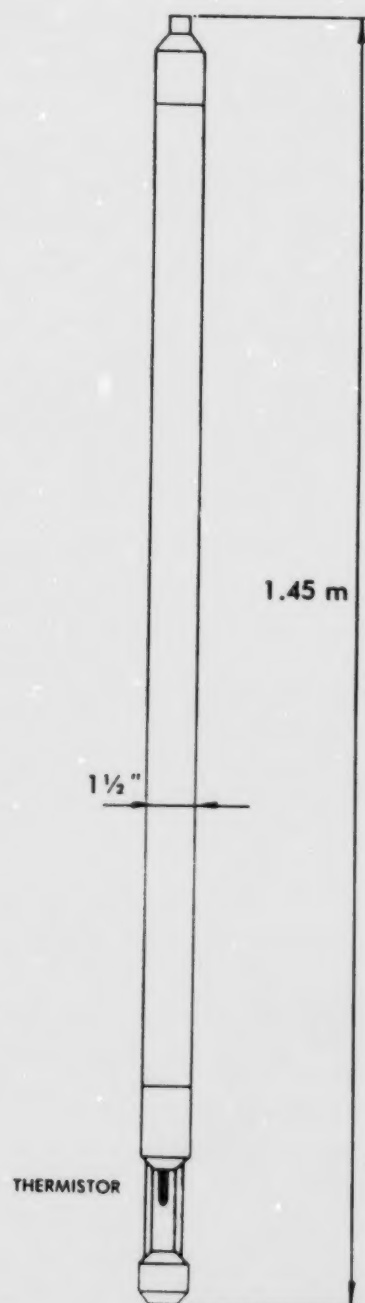
GENERAL SPECIFICATIONS:

Length — 1.45 m (5.5')
Weight — 11 kg (24lb)
Diameter — 3.8 cm (1 1/2")
Temperature — up to 100°C (212°F)
Pressure — up to 210 kg/cm² (3000 psi)

OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000 m (6500')
Hole Diameter — min. 6 cm (2.5"), no maximum
Logging Speed — 9 m/min (30' /min)
Logging Mode — free running, log recorded on entry into borehole

Optimum logging requires that the formations and borehole fluid have been allowed to reach temperature stabilisation before logging begins. Furthermore for this same reason the temperature log should be the first tool into the borehole, and data should be recorded during the entry rather than exit run. The sonde will function in any borehole conditions although open, fluid filled conditions are needed to achieve the formation temperature monitoring usually required.



TECHNICAL INFORMATION:

All three log options are derived simultaneously from measurement of the electrical resistance of a single Thermistor, mounted in a protecting cage at the base of the sonde. Being a calibrated function of temperature this resistance measurement is presented as an absolute temperature log, with optional processing available to look more closely at the nature of the more rapid changes encountered. Specifically:

ABSOLUTE TEMPERATURE

- Borehole temperature seen by the sonde as a function of depth. This is the fundamental temperature log and is needed to properly evaluate any of the other options selected.

TEMPERATURE DIFFERENCE

- is an amplification of features seen on the Absolute log, with rapid changes stripped from the general background Temperature Gradient and presented on a more sensitive scale.

TEMPERATURE DIFFERENTIAL

- is a presentation of the Absolute log differentiated with respect to time. This can be related, through the constant logging speed, to the rate of change of temperature with depth.

PRESENTATION:

Logs may be presented on a variety of metric or imperial vertical scales as required, with the following maximum sensitivities available for the display of each log:

- (a) ABSOLUTE — 0.25°C/minor division
- (b) DIFFERENCE — 0.25°C/minor division
- (c) DIFFERENTIAL — 0.0025°C/sec/minor division

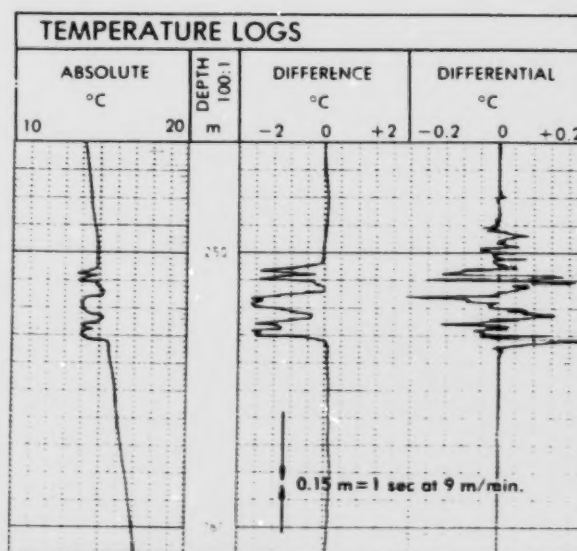


Fig. 1 Presentation Example

APPLICATION SUMMARY:

Temperature logs are used for a variety of purposes, most commonly including:

ABSOLUTE LOGS — Formation temperature for underground-mine planning.

- As an aid to interpretation and correction of other logs, particularly resistivity logs.

DIFFERENTIAL — To identify and help quantify aquifers and fluid flows with the borehole.

NB: If only the Absolute Bottom Hole Temperature is required it may be more simply obtained by running a BHT insert in conjunction with any other sonde.

CO1 CALIPER SONDE

MEASUREMENT:

HOLE DIAMETER (AND HOLE VOLUME)

The CO1 Sonde is a specialist 3-arm caliper device. It is designed to provide a more comprehensive measurement of hole size variations than those afforded by single arm and/or pad devices incorporated into other combination tools. Measurement of borehole volume can also be made, as with all other caliper devices, by the integration of the CO1 hole diameter data over the depth interval of interest.

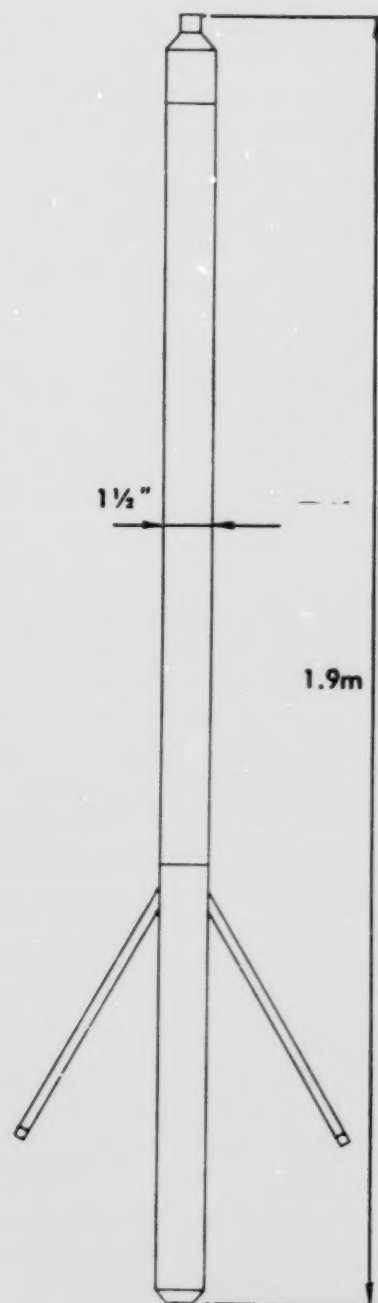
GENERAL SPECIFICATIONS:

Length — 1.90m (6.25')
Weight — 13 kg (28lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — 5 to 45 cm (2 to 18")
Logging Speed — 9m/min (30'/min)
Logging Mode — centralized by the 3 caliper arms

Logging may proceed in any borehole with a diameter accessible by a 1½" diameter sonde. Requirement will usually be in fluid filled, or dry, open hole conditions.



TECHNICAL INFORMATION:

The 3 arms, held in a 'closed' position for borehole entry, are activated into a spring loaded 'open' configuration prior to commencement of the logging run. This arm extension is achieved by means of a surface controlled motor incorporated within the sonde.

The arms move in unison during the logging run, tracking the average diameter of the borehole. Arm movement is translated, through a rack and pinion and potentiometer system, to an electronic signal for surface transmission and recording. The resulting caliper log is linear with hole diameter and sensitive to the smallest of changes in the borehole wall.

Mechanical calibration, both before and after the logging run, enables accurate presentation of the log in either Metric or Imperial units of hole diameter.

Either 'standard' or 'long' caliper arms, all at $\frac{1}{16}$ " diameter with hardened tips to minimise wear, are available to optimise log accuracies over the full operational range.

A log processing option can, by integration of the caliper log, provide a hole volume evaluation.

PRESENTATION:

The Caliper log may be presented on any horizontal and vertical scale in Metric or Imperial units of hole depth and diameter. The curve may be included in a composite presentation with other logs being run, or be presented alone with increased scale sensitivity.

GENERAL LOG				
CALIPER		DEPTH	HOLE VOLUME	
1 2	INCHES 2	SCALE m 200.1	m	US gall
			675.00	8.66
			670.00	10.43
			665.00	20.26
			660.00	30.14
			655.00	40.67
			650.00	50.99
			645.00	61.41
			640.00	72.49
			635.00	82.89
			630.00	93.28
			625.00	103.68
			620.00	114.02
			615.00	124.60
			610.00	135.00
			605.00	145.83
			600.00	156.50
			595.00	167.25
			590.00	177.79
			585.00	189.03
			580.00	210.69
			575.00	231.98
			570.00	247.94
			565.00	259.48
			560.00	271.15
			555.00	281.96
			550.00	292.00
			545.00	306.44
			540.00	317.66
			535.00	328.45
			530.00	339.66
			525.00	351.06
			520.00	362.00
			515.00	372.97
			510.00	383.93
			505.00	401.25
			500.00	413.32

APPLICATION SUMMARY:

The CO1 Sonde is recommended when knowledge of borehole wall conditions is considered to be of paramount importance; most often when it is felt that the single arm (DD1, DR1 sondes) or pad (DR1, DV1 sondes) caliper devices, as incorporated in other combination sondes, will not provide an adequate survey.

RS1 RESISTANCE, SPONTANEOUS POTENTIAL SONDE

(OR SP/RES SONDE)

MEASUREMENTS:

RESISTANCE (SINGLE POINT)
SPONTANEOUS (OR SELF) POTENTIAL

The RS1 Sonde is a dual function, single electrode, non focussed device producing simultaneous measurement of formation Potential and Resistance.

GENERAL SPECIFICATIONS:

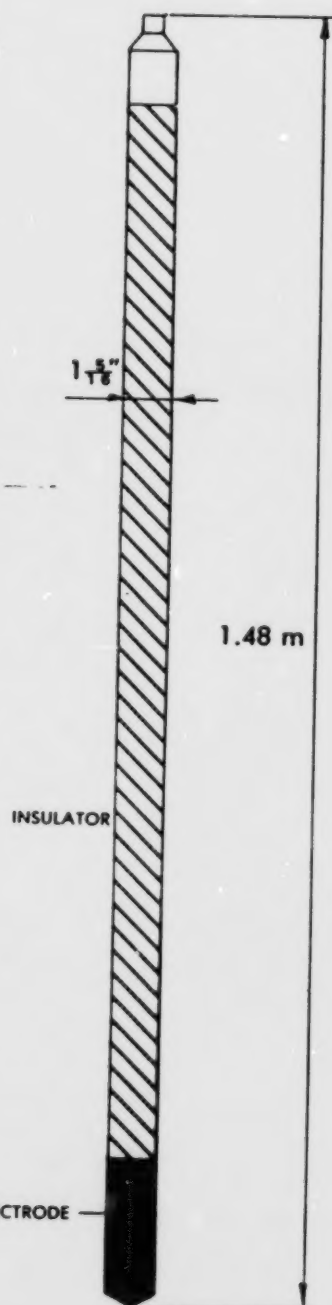
Length — 1.48 m (4.8')
Weight — 6 kg (13 lbs)
Diameter — 3.3 cm (1 $\frac{3}{8}$ ")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx.: 2000 m (6500')
Hole Diameter — open hole: 4 cm to 30+ cm (1.6" to 12+")
Logging Speed — standardly: 9m/min (30' /min)
Logging Mode — free running

Open, fluid filled holes are a prerequisite for both of these electric logs.

Having the lowest replacement value of any BPB sonde, and utilizing no radioactive materials, the RS1 is often used as a first run to assess borehole conditions in unknown or suspect formations.



TECHNICAL INFORMATION:

The Spontaneous Potential (SP) log is a record of the natural electrical potentials developed between the borehole fluid and the surrounding formations. SP's are generated either by electrochemical e.m.f.'s at the junction of dissimilar materials, or by electrokinetic e.m.f.'s developed when fluid moves through a permeable medium.

The Resistance (Res) log is a record of the resistance of the formations between a downhole electrode and a surface fish. It is a useful qualitative log with high vertical resolution and shallow depth of investigation.

PRESENTATION:

Logs may be recorded in metric or imperial units of depth and are available for presentation with full flexibility of vertical and horizontal scales.

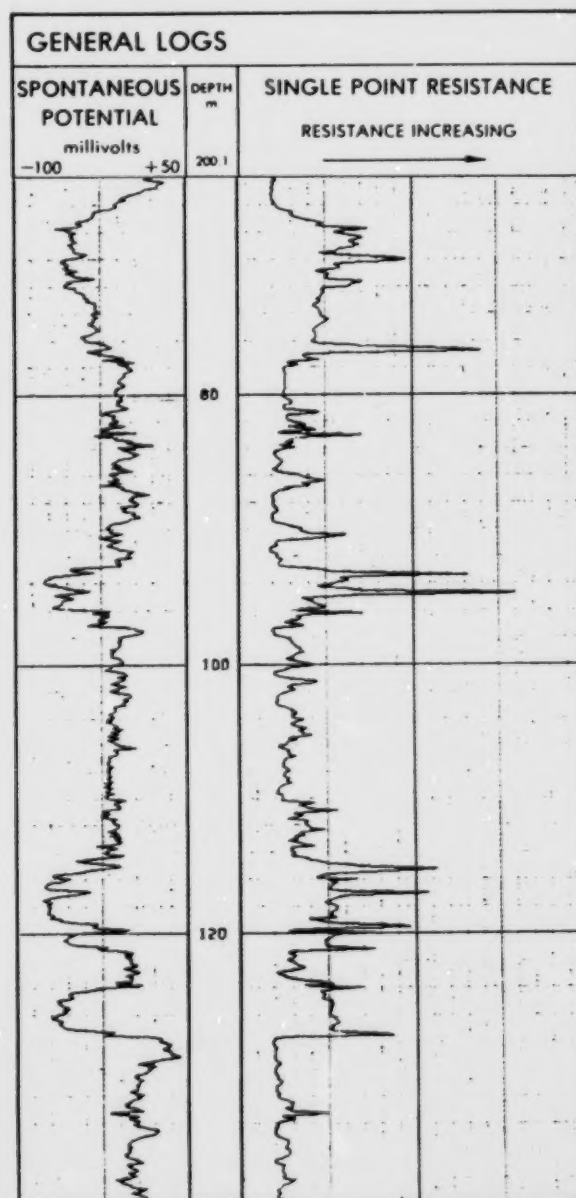
The Spontaneous Potential measurement is presented on a millivolts scale with reference to the ground electrode.

The Resistance log is presented as an uncalibrated indicator of formation resistivities.

APPLICATION SUMMARY:

The SP log is used for geological correlation, bed thickness determination and to differentiate between porous and non porous rocks in sandstone-shale and carbonate-shale sequences. Streaming potentials associated with zones gaining or losing water are sometimes detected.

The Resistance log is very useful for lithology correlation and as a fluid level and casing shoe indicator, with high vertical resolution for the determination of bed thickness. The ROI Focussed Electric Sonde should, however, be selected whenever quantitative resistivity measurements are required, see Subsurface leaflet No. 4.



NN1 DUAL NEUTRON, GAMMA RAY, SONDE.

(OR DSN)

MEASUREMENTS:

RATIO NEUTRON POROSITY
SHORT SPACING NEUTRON (SSN)
LONG SPACING NEUTRON (LSN)
GAMMA RAY

The NN1 Sonde provides dual spacing Neutron (as also available from separate runs of the NO1 Sonde), Neutron Porosity and Gamma Ray logging in a single package. Furthermore, the Ratio based porosity measurement provides a degree of compensation, linearity and caliper independency not possible from a single detector system.

GENERAL SPECIFICATIONS:

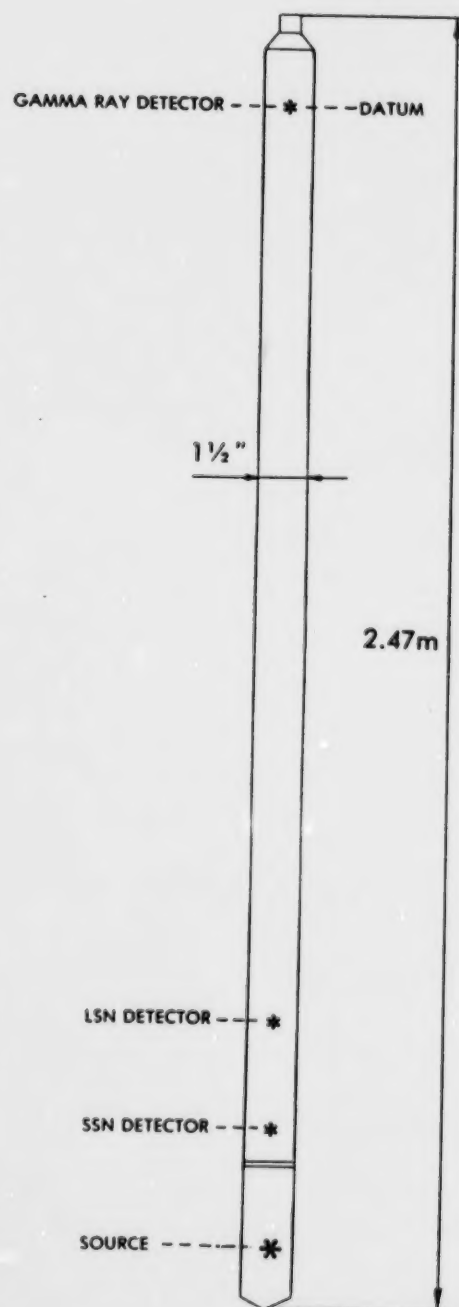
Length — 2.47 m (8.10')
Weight — 14 kg (30 lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

OPERATING CONDITIONS:

Hole Depth — to a max. of approx.: 2000 m (6500')
Hole Diameter — open hole: 6.0 to 30 cm (2.5" to 12")
 casing or rods: 5.0 to 30 cm (2.0" to 12")

Logging Speed — standardly: 9m/min (30' /min)
 detail logging: 2.25m/min (7.5' /min)
Logging Mode — free running

Optimum calibration of Neutron Porosity, based in the NN1 system on the ratio of Long and Short spacing logs, requires open fluid filled holes in reasonable condition. Valuable, although more qualitative logging will continue to be feasible in dry holes, through casing or drill rods and at increased diameters.



TECHNICAL INFORMATION:

The Neutron Log is, in a fluid filled borehole, a measure of the ability of the formation to absorb thermal neutrons. This ability is a function of hydrogen in the formation and, therefore, after correction for borehole effects, the Neutron Log may be presented as an Index of Hydrogen and/or in turn as a measurement of formation porosity. High energy neutrons are emitted through 360° around the logging source. In a fluid filled hole these fast neutrons are slowed down (or thermalised) in a region very close to the source. In an air filled hole thermalisation and absorption both take place in the formation.

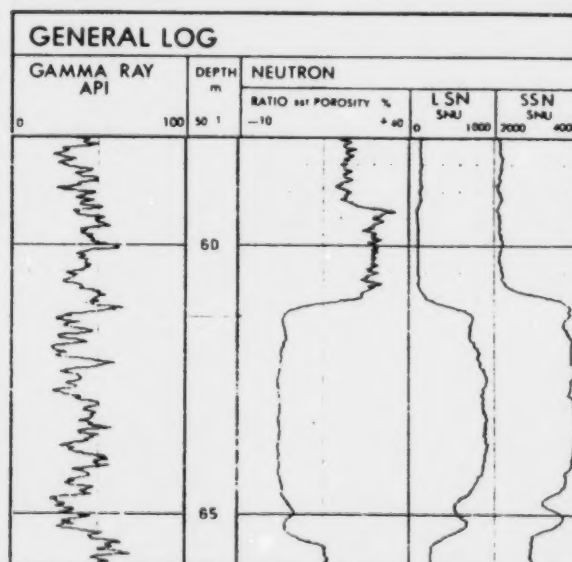
Both Neutron Detectors are uncollimated Helium₃ Tubes and are spaced 45 cms (Long Spacing) and 25 cms (Short Spacing) from the logging source. Calibration uses portable passive jigs to allow log presentation in calibrated units for all three outputs. The LSN and SSN are available as individual logs if required, although the Ratio Log provides the definitive porosity measurement.

SOURCE — a double encapsulated sealed source of Americium 241/Beryllium at an activity of One Curie is mounted in a stainless steel holder and locked securely to the sonde during logging operations. The source holder is transported in a purpose designed shield with a maximum surface radiation level of 2 mR/hr (gamma) and 6 mR/hr (Neutron).

The Gamma Ray system is identical to that described in the DD1 leaflet No. 1.

PRESENTATION:

A range of presentations of Ratio Porosity, SSN, LSN, and Gamma Ray logs are available with a full flexibility of format and vertical and horizontal scales.



APPLICATION SUMMARY:

- RATIO** — Lithology Identification and Correlation and, in open fluid filled holes, Hydrogen Index/Porosity measurement for quantitative formation evaluation.
- SSN** — Porosity indication plus high resolution Lithology Identification, Correlation and Bed Thickness evaluation; particularly useful in higher apparent porosity formations.
- LSN** — Porosity indication plus Lithology Identification and Correlation.

Neutron logs are also being used, through empirically established relationships, for Strength and Fracture analysis of coal measure formations.

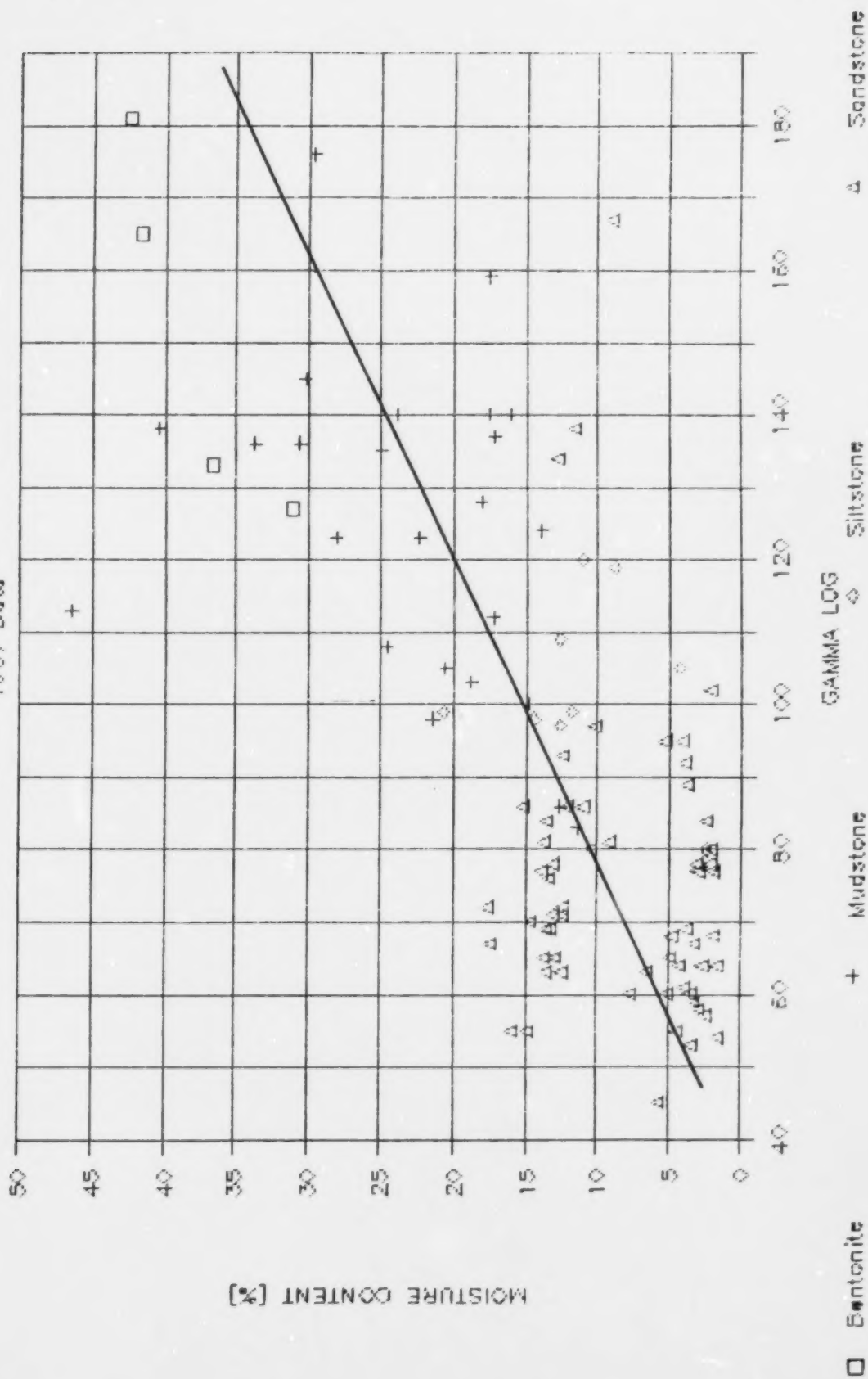
GAMMA RAY — Shale content, Lithology Identification and Correlation.

The NN1 Sonde is seen as a comprehensive porosity and lithology evaluation package, suited to the full range of slim hole environments. In addition its physical dimensions and the nature of its measurements make the NN1 particularly useful for qualitative logging in less than optimum conditions, e.g. through casing or drill rods, or in dry holes.

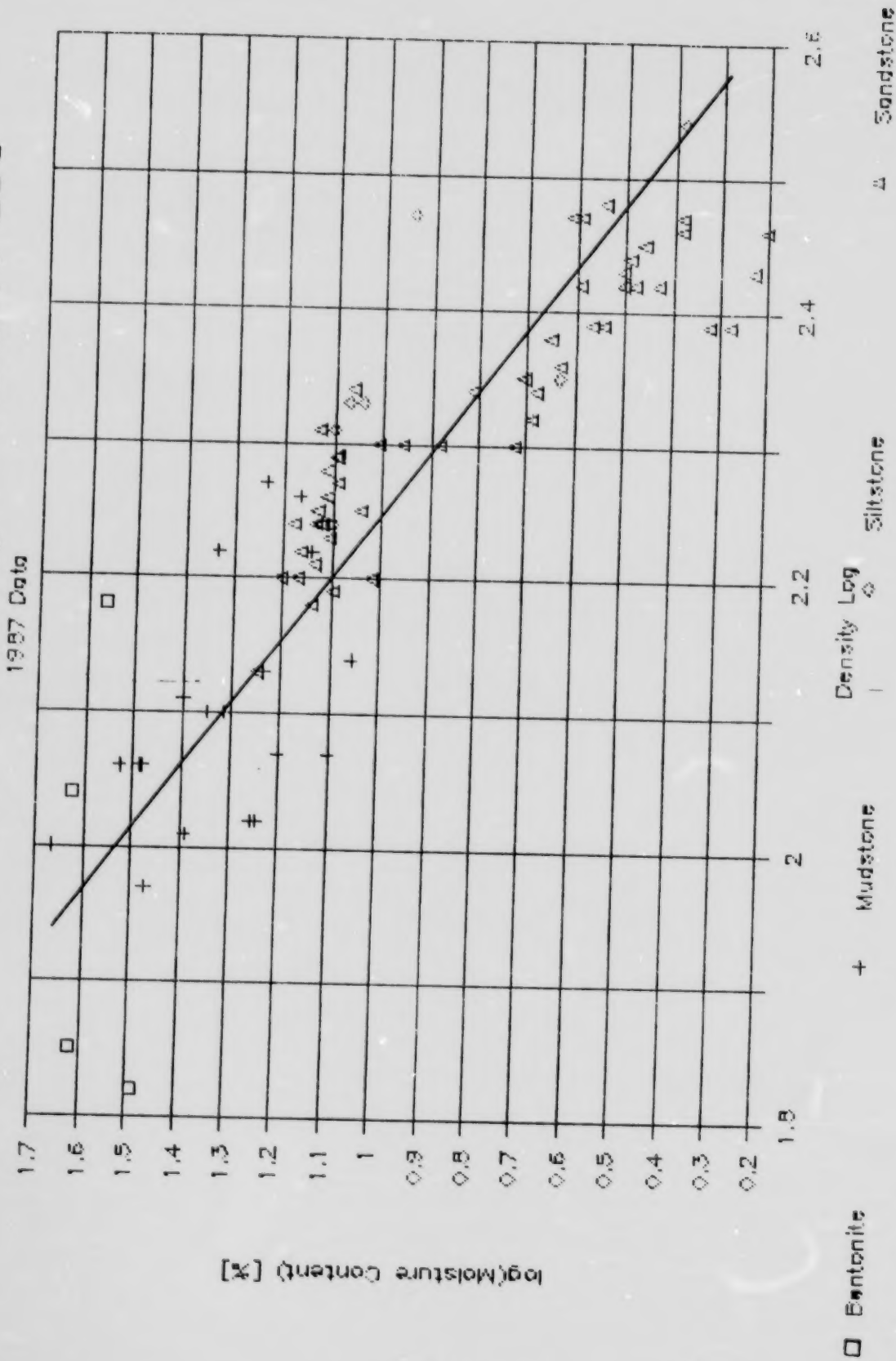
APPENDIX III

GEOTECHNICAL COAL CORRELATIONS

1987 2061

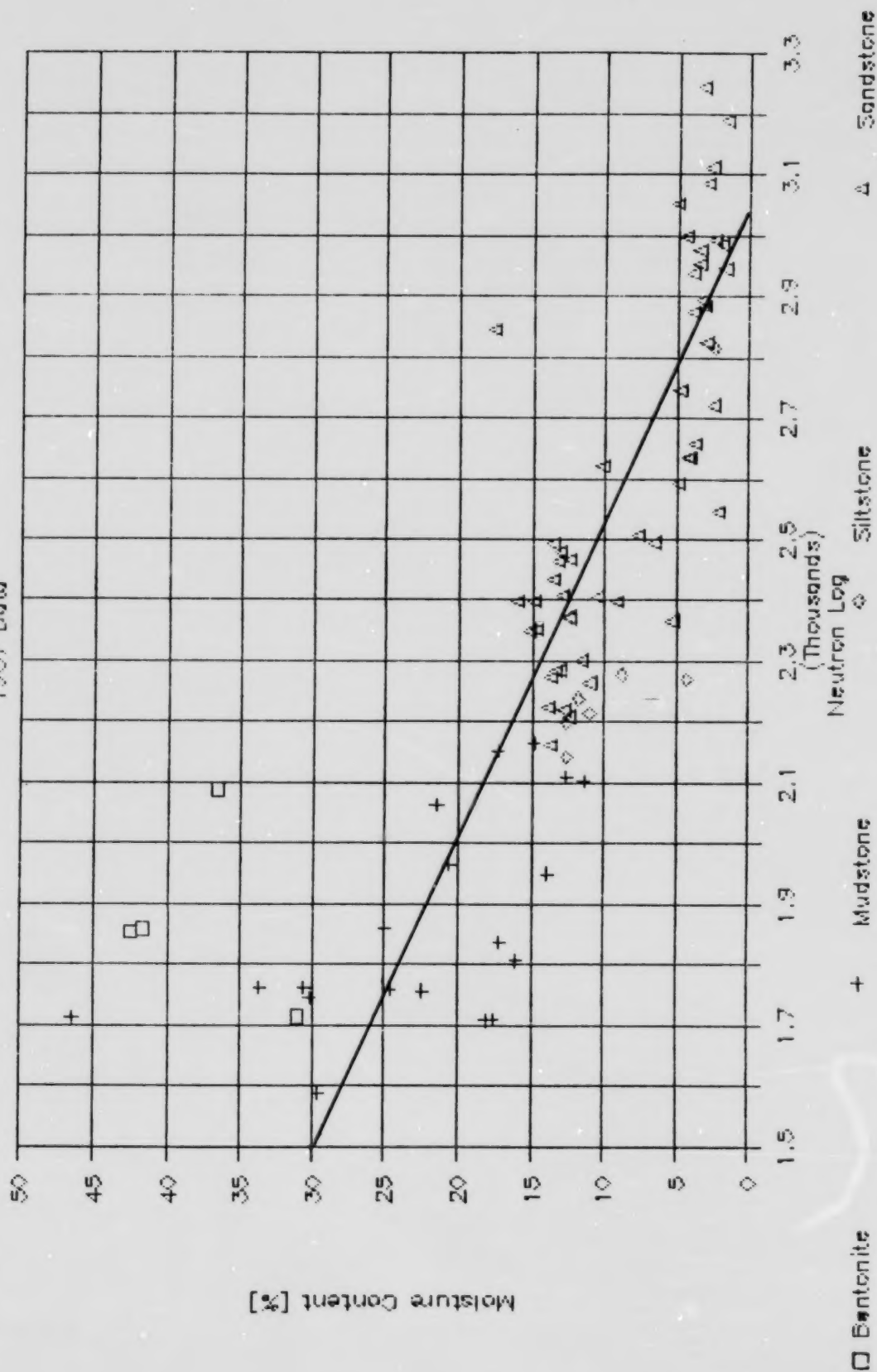


log(MOISTURE CONTENT) vs DENSITY LOG



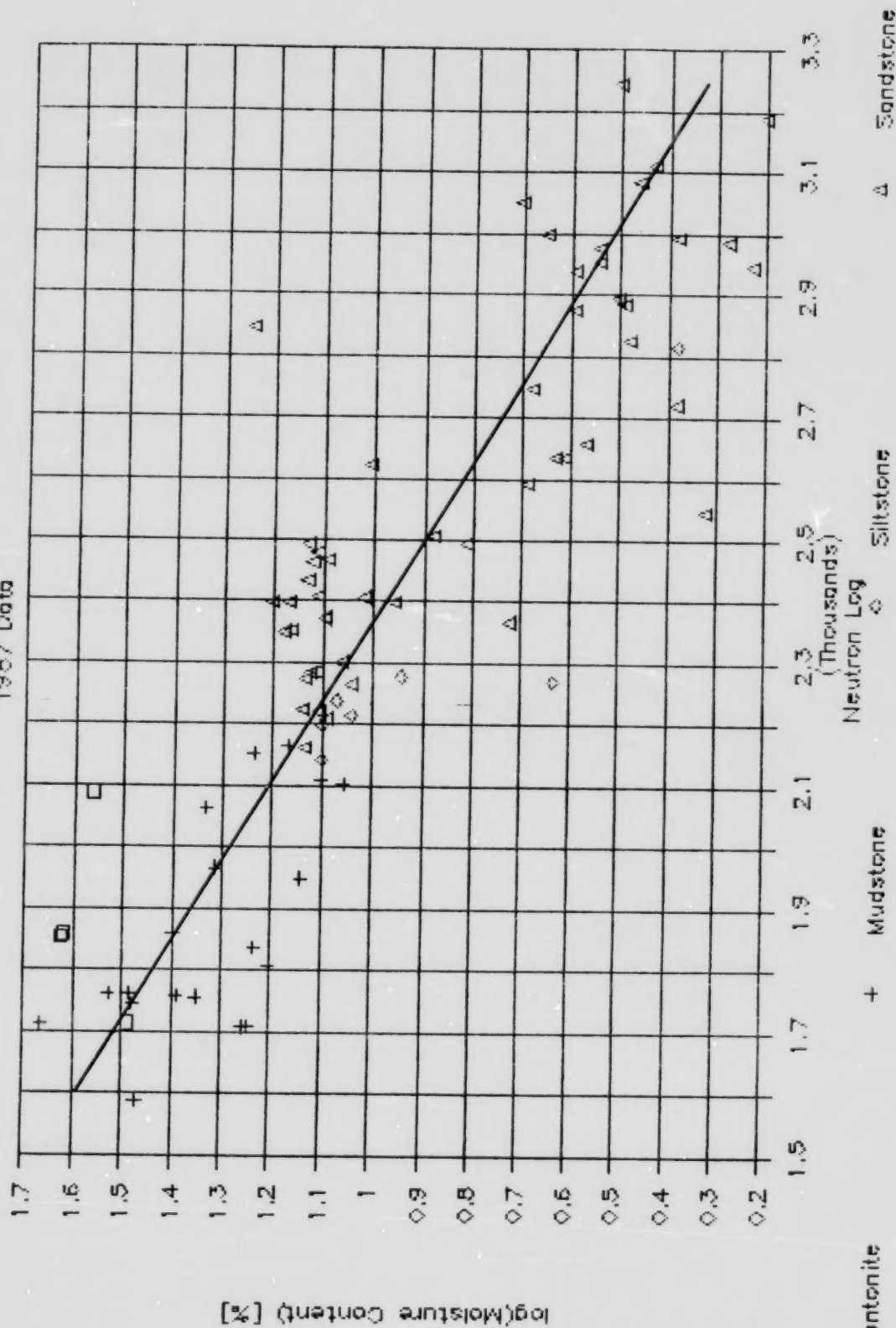
MOISTURE CONTENT vs NEUTRON LOG

1960-61



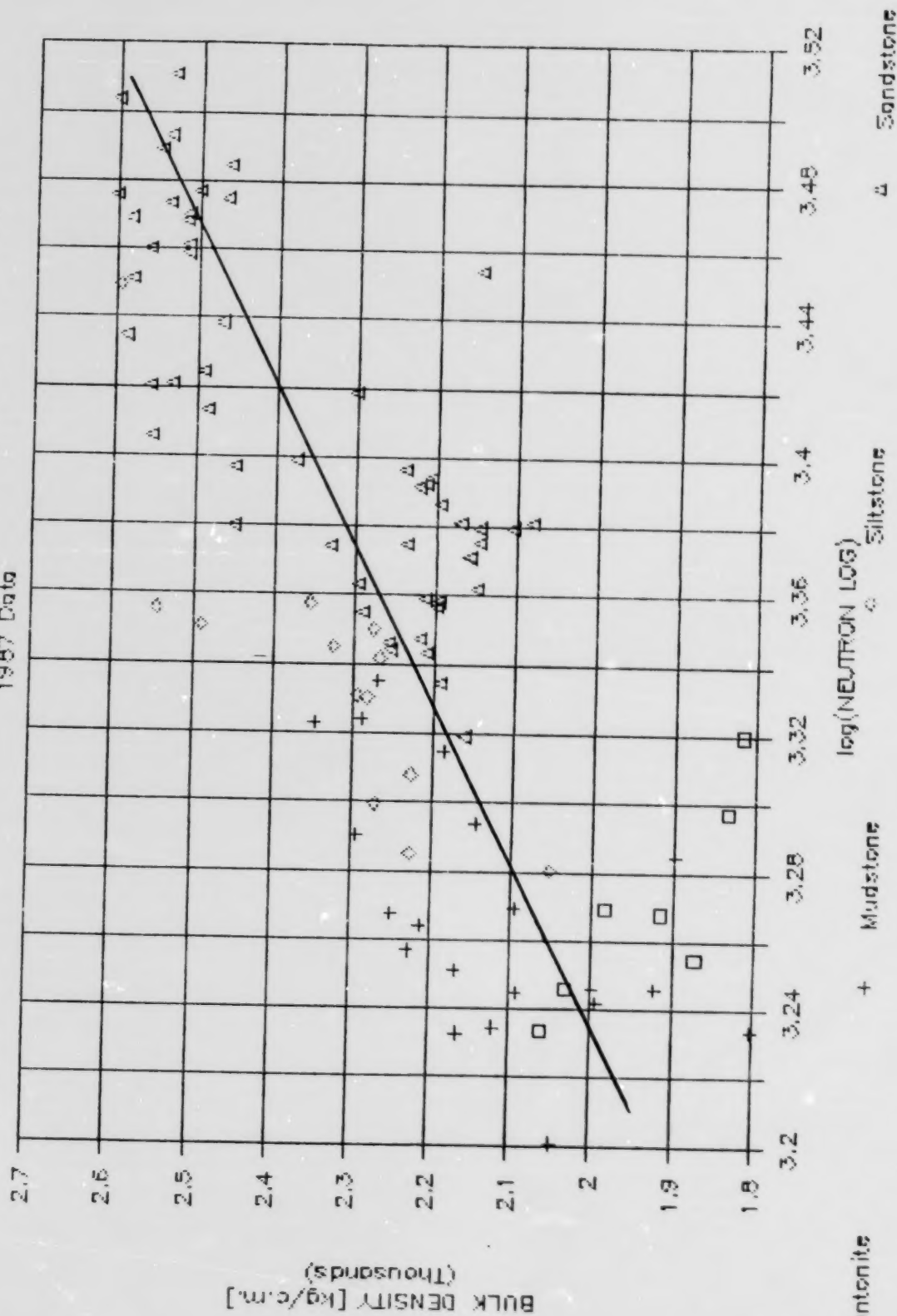
log(MOISTURE CONTENT) VS NEUTRON LOG

1987 Data



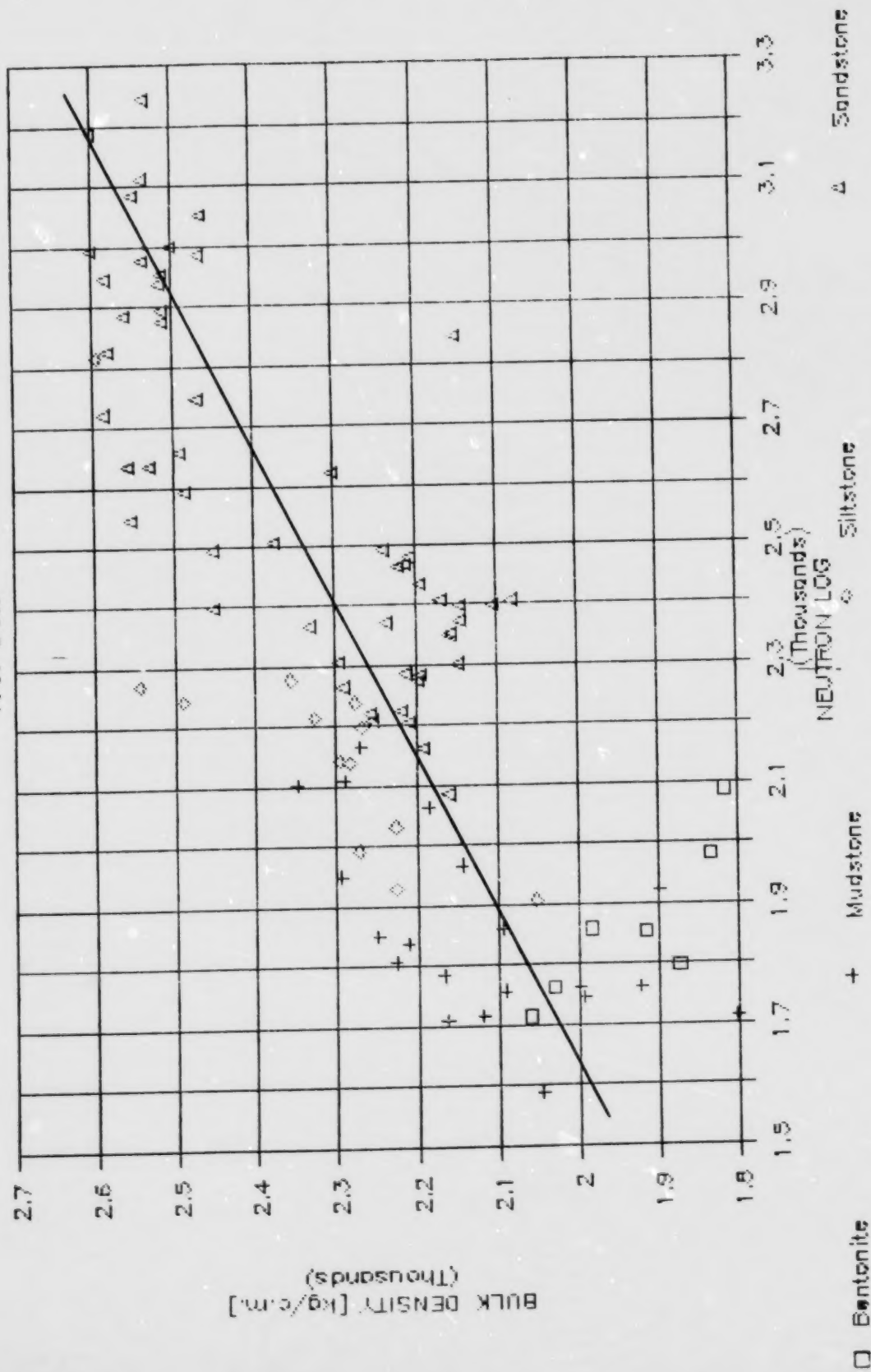
BULK DENSITY vs log(NEUTRON LOG)

1987 Data



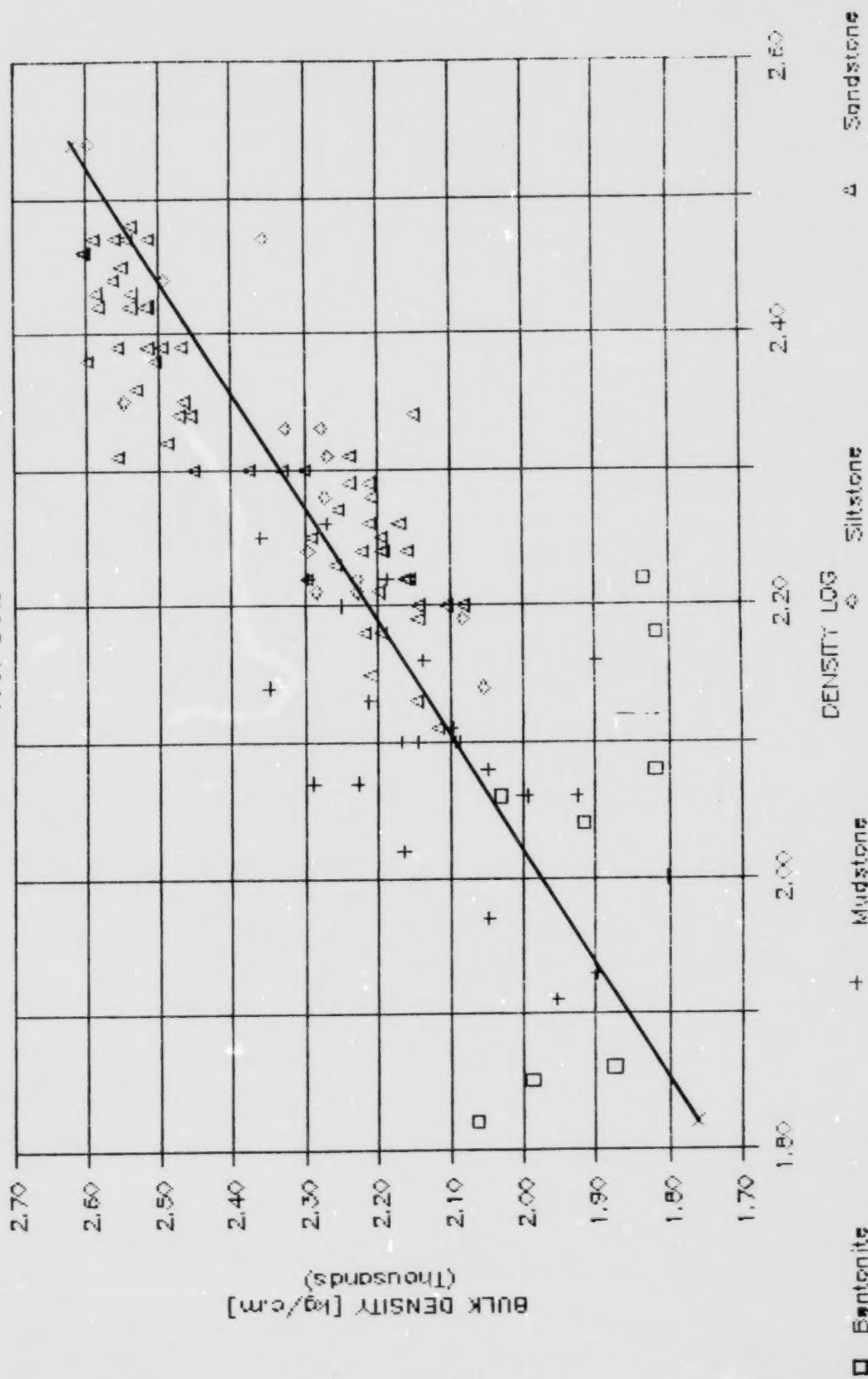
BULK DENSITY VS NEUTRON LOG

1987 Data



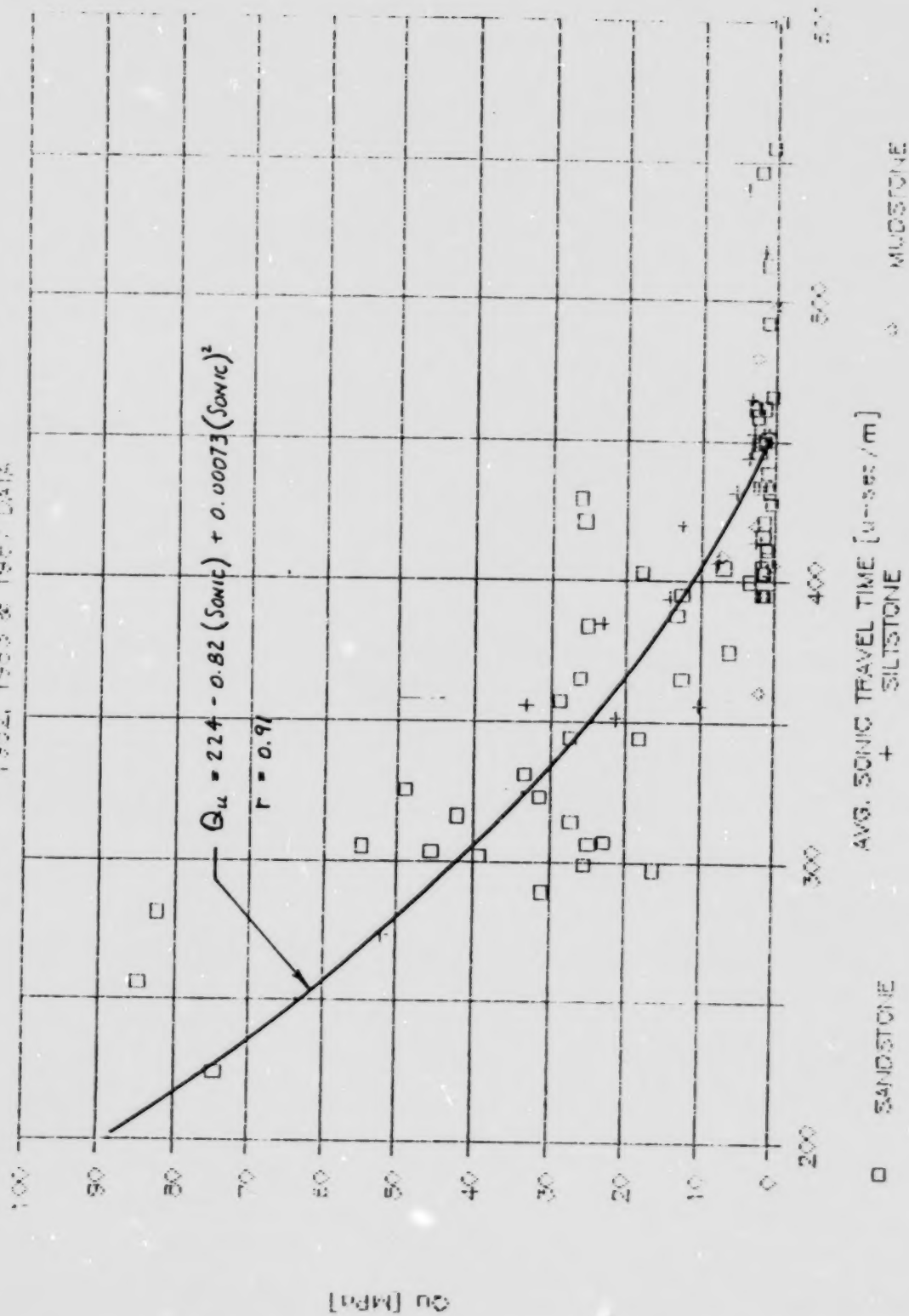
BULK DENSITY VS DENSITY LOG

1987 Data



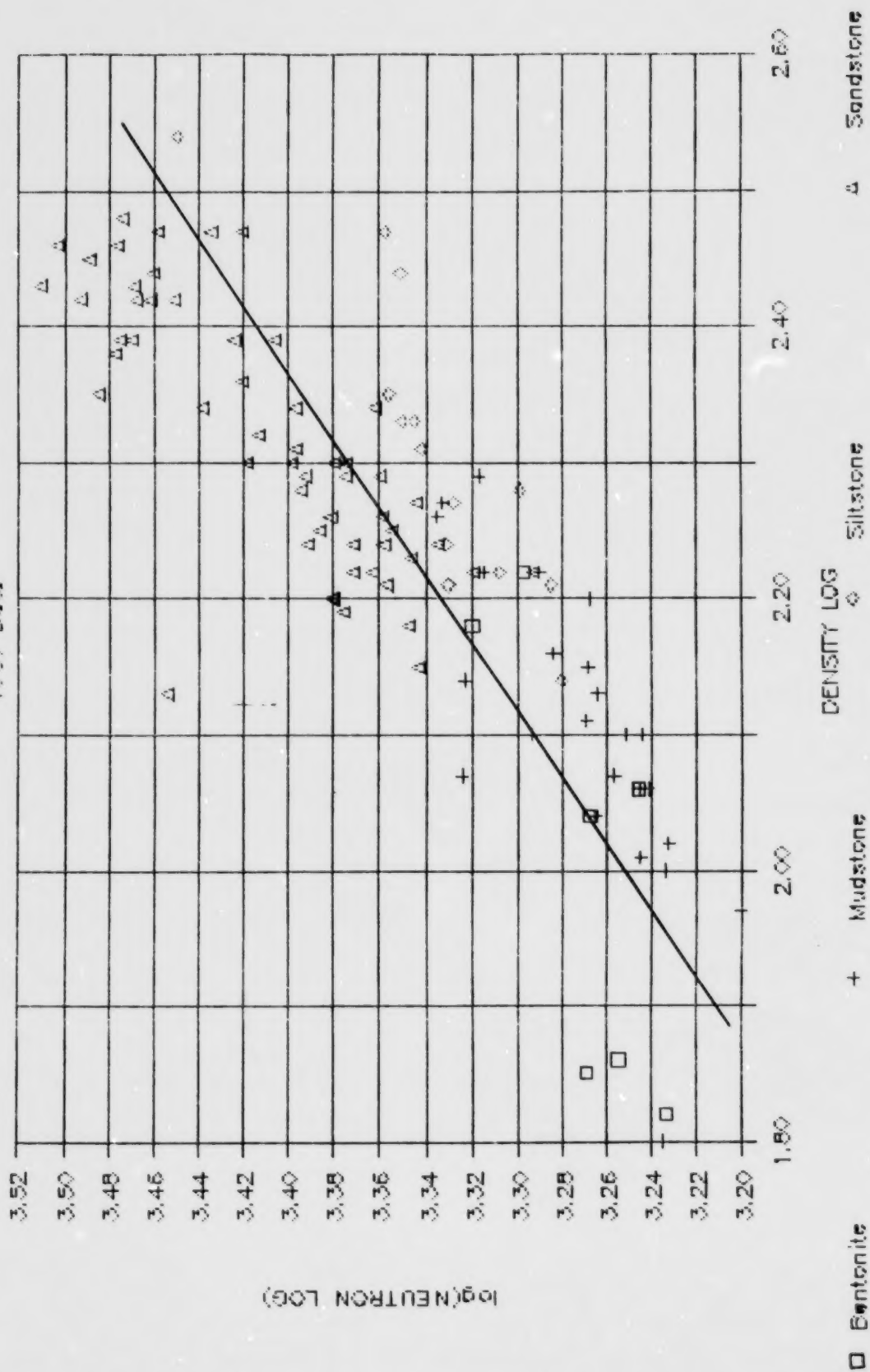
Qu vs SONIC TRAVEL TIME

1992, 1993 & 1997 DATA



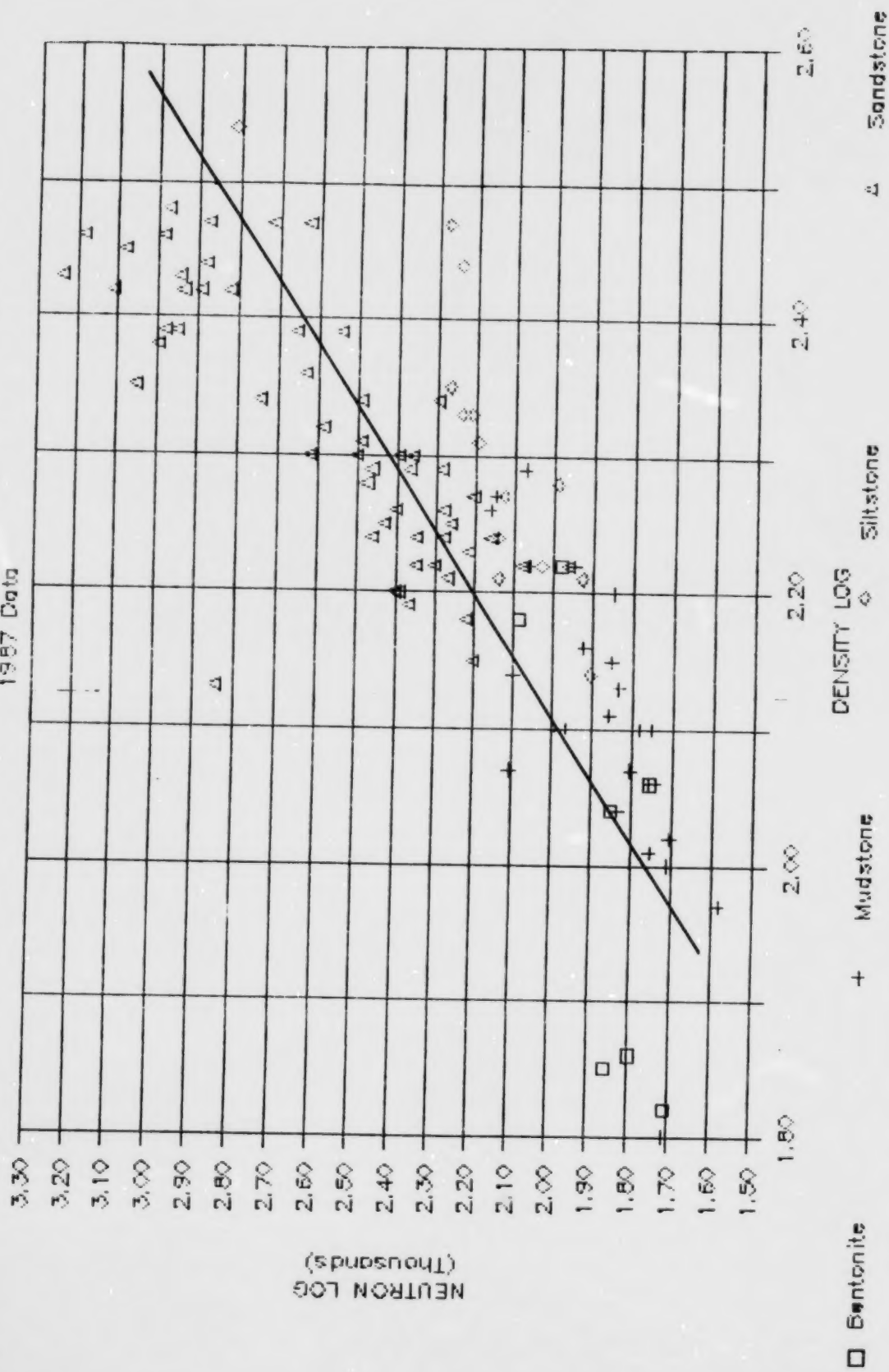
log(NEUTRON) vs DENSITY LOG

1987 Data



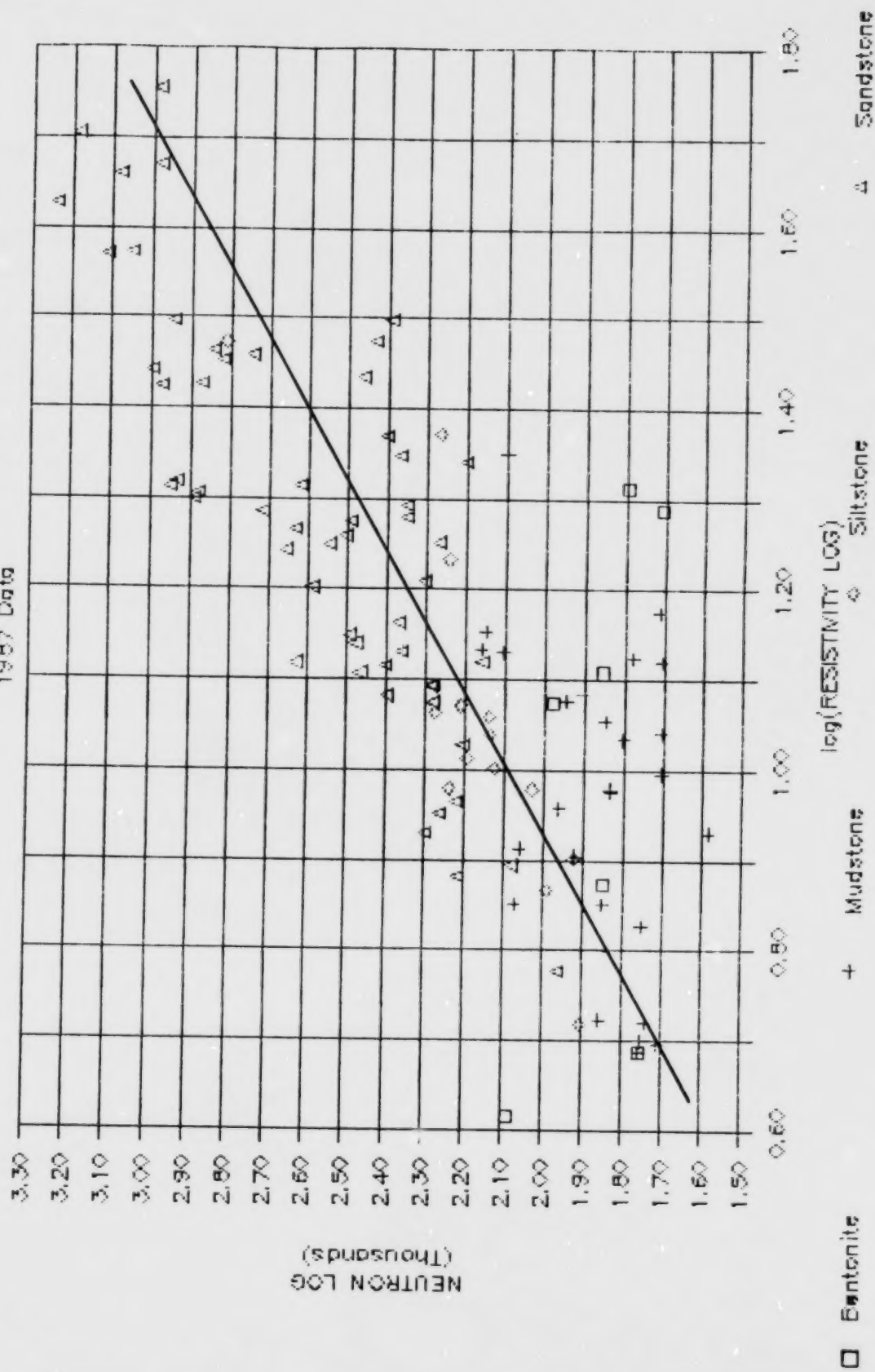
NEUTRON LOG VS DENSITY LOG

1987 Data



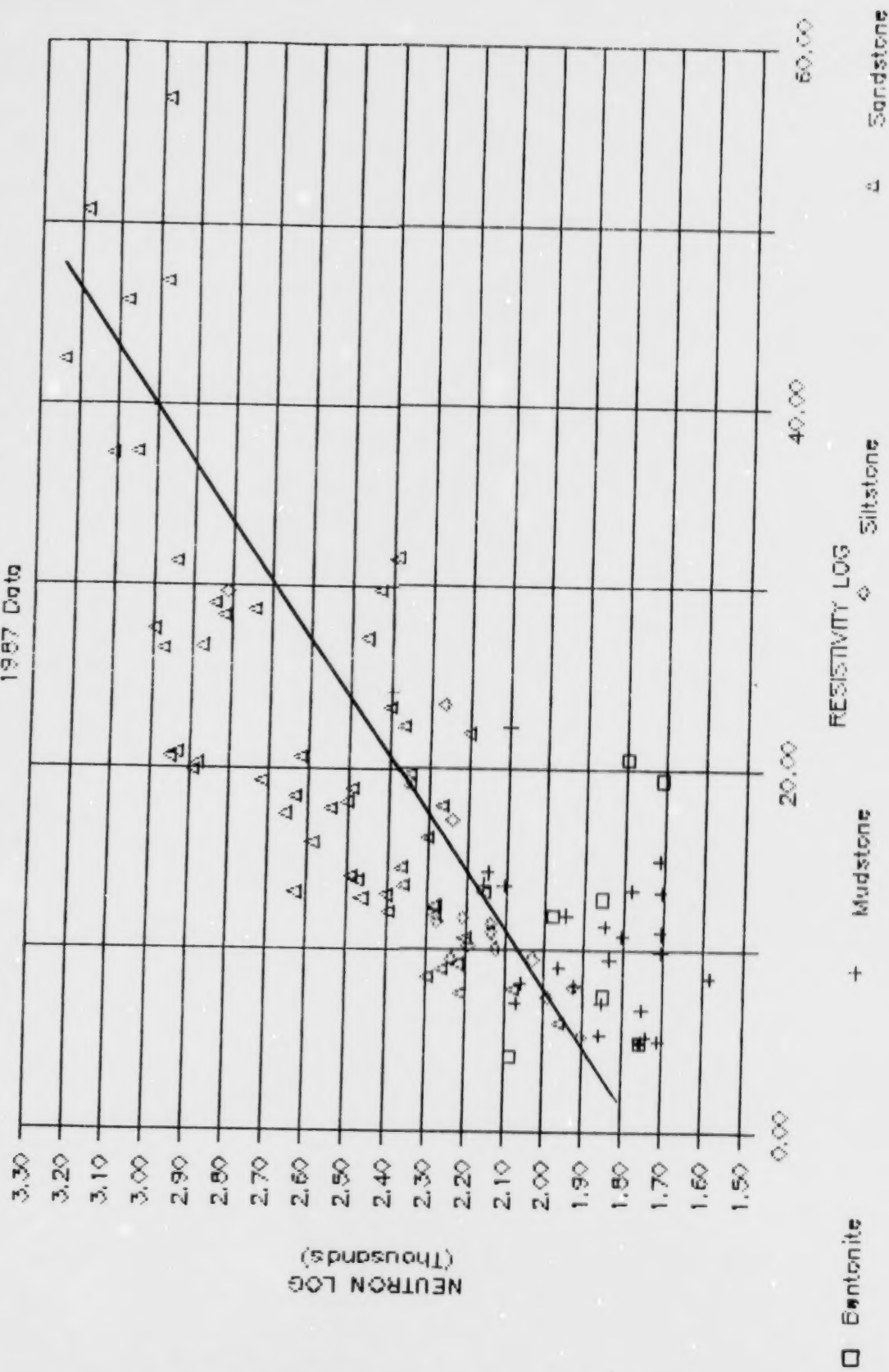
NEUTRON vs log(RESISTIVITY)

1987 Data



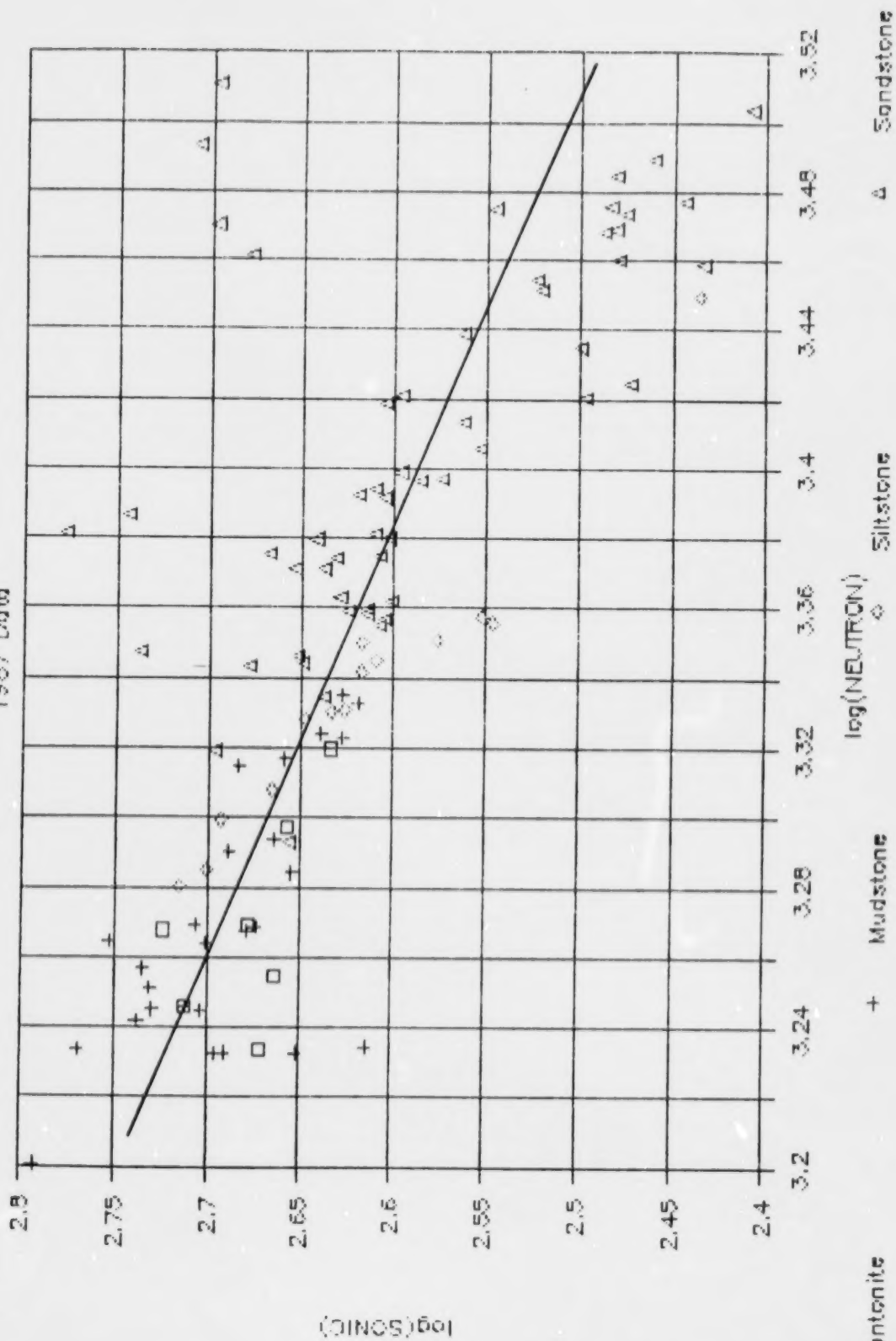
NEUTRON LOG VS RESISTIVITY LOG

1987 Data



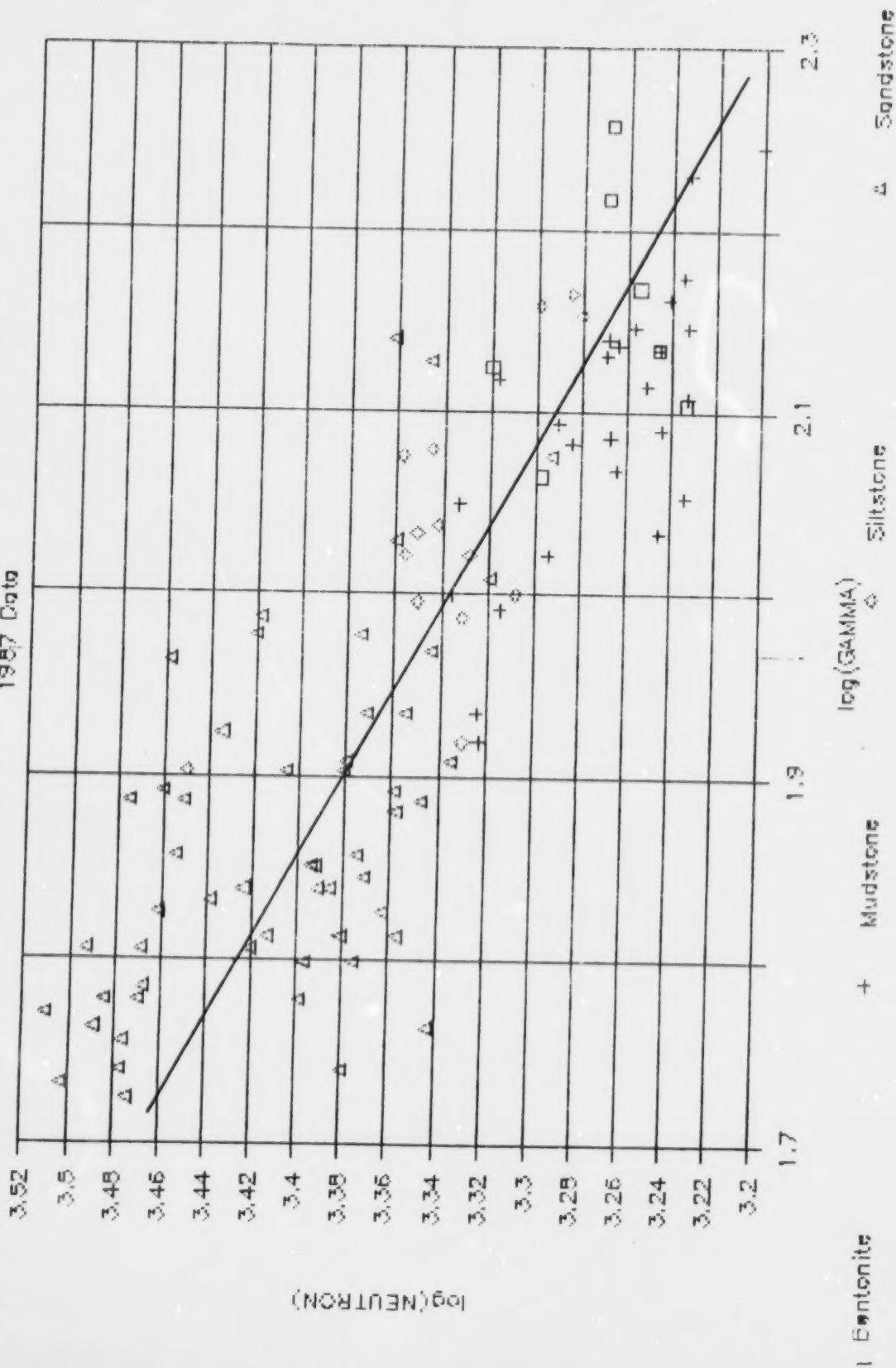
log(SONIC) vs log(NEUTRON)

1987 Data



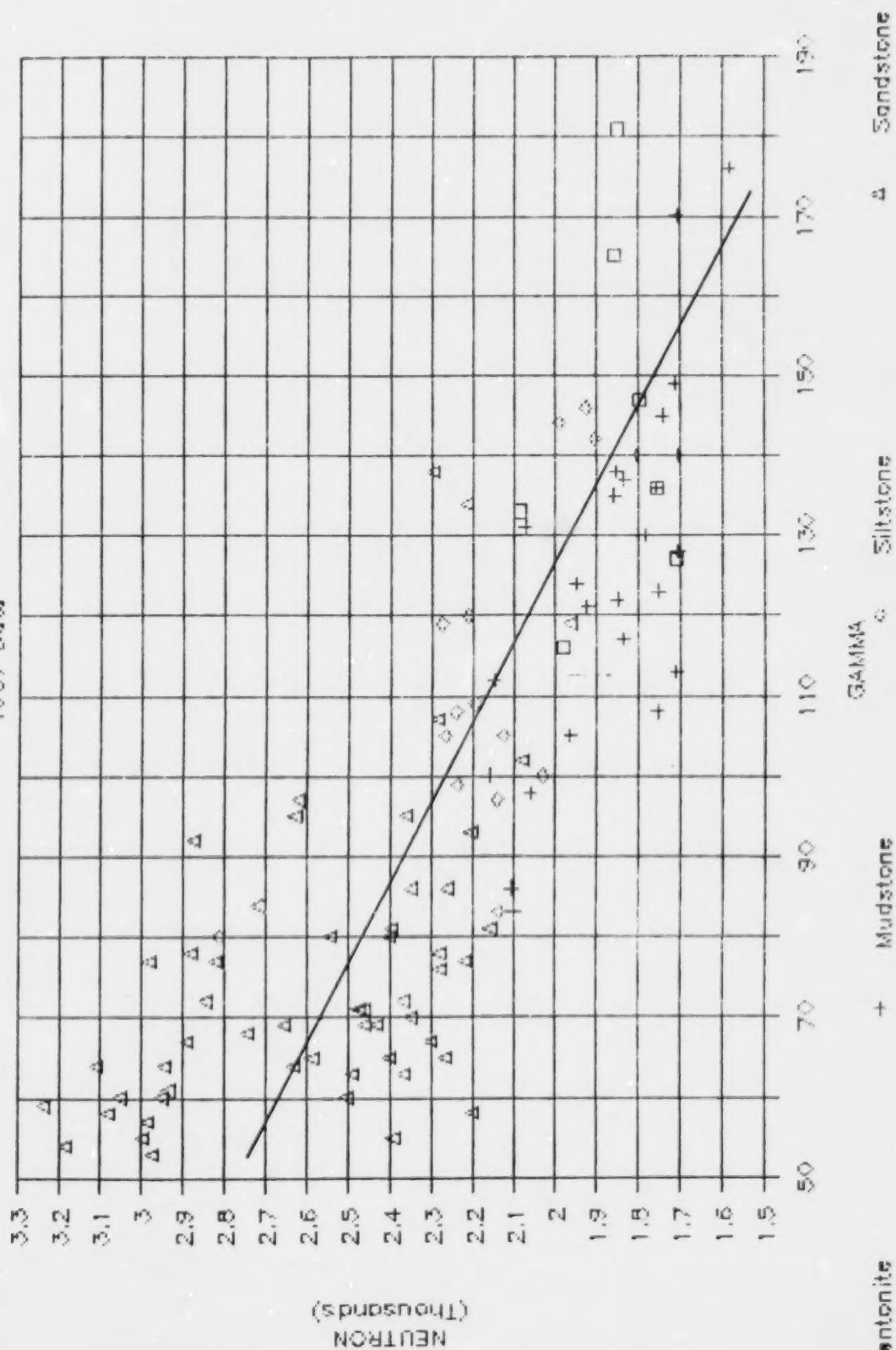
log(NEUTRON) vs log(GAMMA)

1987 Data



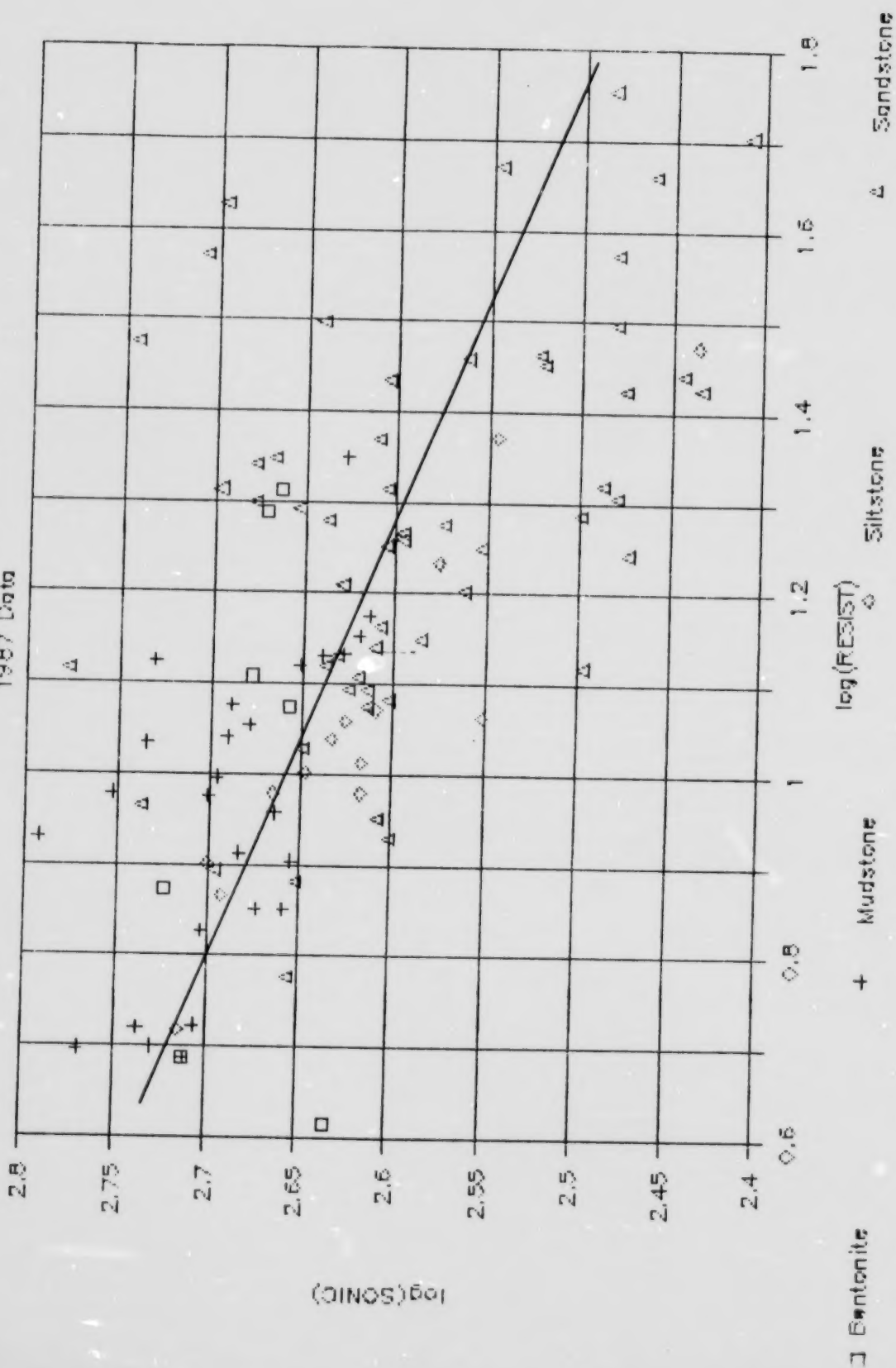
NEUTRON VS GAMMA

1987 Data



log(SONIC) vs log(RESIST)

1987 Data



BV25:

READY

	BH	BI	BJ	BK	BL	BT	BU	BV
7	log(NEUT) vs log(GAMMA)							
8	Regression Output:							
9	Constant		4.236617					
10	Std Err of Y Est		0.043187					
11	R Squared		0.697256	R=0.835				
12	No. of Observations		105					
13	Degrees of Freedom		103					
14								
15	X Coefficient(s)	-0.44942						
16	Std Err of Coef.	0.029179						
17								
18								
19	SONIC vs RESISTIVITY							
20	Regression Output:							
21	Constant		501.3026					
22	Std Err of Y Est		65.54834					
23	R Squared		0.313358	R=0.560				
24	No. of Observations		105					
25	Degrees of Freedom		103					
26	23-Mar-88 08:49 PM							

BV45:

READY

	BH	BI	BJ	BK	BL	BT	BU	BV
26								
27	X Coefficient(s)	-4.17499						
28	Std Err of Coef.	0.608950						
29								
30								
31	log(SONIC) vs log(RESIST)							
32	Regression Output:							
33	Constant		2.858871					
34	Std Err of Y Est		0.066186					
35	R Squared		0.380009	R=0.616				
36	No. of Observations		105					
37	Degrees of Freedom		103					
38								
39	X Coefficient(s)	-0.20172						
40	Std Err of Coef.	0.025388						
41								
42								
43	SONIC vs NEUTRON							
44	Regression Output:							
45	Constant		738.6543					
46	23-Mar-88 08:50 PM							

V65:

READY

	BH	BI	BJ	BK	BL	BT	BU	BV
46	Std Err of Y Est		55.65467					
47	R Squared		0.504994	R=0.711				
48	No. of Observations		105					
49	Degrees of Freedom		103					

CD24:

READY

	AZ	BA	BB	BC	BD	CD	CE	CF
5	log(Neutron) vs log(Resist)							
6	Regression Output:							
8	Constant			3.079926				
9	Std Err of Y Est			0.049580				
10	R Squared			0.600995	R=0.775			
11	No. of Observations			105				
12	Degrees of Freedom			103				
13								
14	X Coefficient(s)	0.236891						
15	Std Err of Coef.	0.019018						
16								
17								
18	log(Neut/St) vs log(Resist)							
19	Regression Output:							
20	Constant			1.057950				
21	Std Err of Y Est			0.045882				
22	R Squared			0.534783	R=0.73			
23	No. of Observations			105				
24	Degrees of Freedom			103				
25	13-Mar-88 08:52 PM							

CD44:

READY

	AZ	BA	BB	BC	BD	CD	CE	CF
26	X Coefficient(s) 0.191514							
27	Std Err of Coef. 0.017600							
28								
29								
30	log(Neut/Res) vs log(Sonic)							
31	Regression Output:							
32	Constant			-9.00345				
33	Std Err of Y Est			0.587210				
34	R Squared			0.301950	R=0.55			
35	No. of Observations			105				
36	Degrees of Freedom			103				
37								
38	X Coefficient(s)	4.594533						
39	Std Err of Coef.	0.688332						
40								
41								
42	SONIC vs GAMMA							
43	Regression Output:							
44	Constant			305.7907				
45	13-Mar-88 08:52 PM							

CD64:

READY

	AZ	BA	BB	BC	BD	CD	CE	CF
46	Std Err of Y Est			66.84024				
47	R Squared			0.286025	R=0.535			
48	No. of Observations			105				
49	Degrees of Freedom			103				
50								
51	X Coefficient(s)	1.278727						

54 SONIC vs NEUT/GAMMA
 55 Regression Output:
 56 Constant 530.6613
 57 Std Err of Y Est 63.13370
 58 R Squared 0.363015 R=0.603
 59 No. of Observations 105
 60 Degrees of Freedom 103

62 X Coefficient(s) -3.64886
 63 Std Err of Coef. 0.476257
 64

23-Mar-88 08:52 PM

CD84:

READY

55 AZ BA BB BC BD CD CE CF

56 SONIC vs log[NEUT/GAMMA]
 67 Regression Output:
 68 Constant 746.4099
 69 Std Err of Y Est 62.00604
 70 R Squared 0.385566 R=0.621
 71 No. of Observations 105
 72 Degrees of Freedom 103
 73

74 X Coefficient(s) -227.670
 75 Std Err of Coef. 28.31888
 76
 77

78 SONIC vs NEUT*GAMMA
 79 Regression Output:
 80 Constant 341.4951
 81 Std Err of Y Est 76.82715
 82 R Squared 0.056729 R=0.238
 83 No. of Observations 105
 84 Degrees of Freedom 103

23-Mar-88 08:53 PM

CD104:

READY

85 AZ BA BB BC BD CD CE CF

86 X Coefficient(s) 0.000421
 87 Std Err of Coef. 0.000169
 88
 89

90 SONIC vs NEUT*RESIST/GAMMA
 91 Regression Output:
 92 Constant 471.0086
 93 Std Err of Y Est 66.31210
 94 R Squared 0.297264 R=0.545
 95 No. of Observations 105
 96 Degrees of Freedom 103
 97

98 X Coefficient(s) -0.07017
 99 Std Err of Coef. 0.010631

102 NEUTRON vs GAMMA
 103 Regression Output:
 104 Constant 3284.468

23-Mar-88 09:57 PM

	AZ	BA	BB	BC	BD	CD	CE	CF
105	Std Err of Y Est		248.4082					
106	R Squared		0.647110		R=0.804			
107	No. of Observations		105					
108	Degrees of Freedom		103					
110	X Coefficient(s)		-10.1675					
111	Std Err of Coef.		0.739820					
114	log(NEUTRON) vs GAMMA							
115	Regression Output:							
116	Constant		3.544292					
117	Std Err of Y Est		0.044354					
118	R Squared		0.680671		R=0.825			
119	No. of Observations		105					
120	Degrees of Freedom		103					
122	X Coefficient(s)		-0.00195					
123	Std Err of Coef.		0.000132					
124								
125	23-Mar-88 09:03 PM							

(X32:

READY

	AO	AP	AQ	AR	AS	BX	BY	BZ
14	Neut/Gam vs DENLOG							
15	Regression Output:							
16	Constant		-98.4153					
17	Std Err of Y Est		9.532734					
18	R Squared		0.467361		R=0.68			
19	No. of Observations		105					
20	Degrees of Freedom		103					
22	X Coefficient(s)		56.20578					
23	Std Err of Coef.		5.912247					
26	log(Neut/Gam) vs DENLOG							
27	Regression Output:							
28	Constant		-0.83734					
29	Std Err of Y Est		0.147033					
30	R Squared		0.535531		R=0.73			
31	No. of Observations		105					
32	Degrees of Freedom		103					
33	23-Mar-88 09:05 PM							

X52:

READY

	AO	AP	AQ	AR	AS	BX	BY	BZ
34	X Coefficient(s)		0.993769					
35	Std Err of Coef.		0.091191					
38	log(Neut/Gam) vs log(DENLOG)							
39	Regression Output:							
40	Constant		-0.34305					
41	Std Err of Y Est		0.147682					

45 X Coefficient(s) 4.959617
 46 Std Err of Coef. 0.458876
 47
 48
 49 Neut*Gam vs DENLOG
 50 Regression Output:
 51 Constant 404995.2
 52 Std Err of Y Est 42595.58
 23-Mar-88 09:05 PM

BX72:

READY

	AO	AP	AQ	AR	AS	BX	BY	BZ
53	R Squared			0.092473	R=0.30			
54	No. of Observations			105				
55	Degrees of Freedom			103				
56								
57	X Coefficient(s)	-85584.8						
58	Std Err of Coef.	26417.98						
59								
60								
61	GAMMA vs RESIST							
62	Regression Output:							
63	Constant			131.3596				
64	Std Err of Y Est			25.60501				
65	R Squared			0.401027	R=0.63			
66	No. of Observations			105				
67	Degrees of Freedom			103				
68								
69	X Coefficient(s)	-1.97536						
70	Std Err of Coef.	0.237872						

23-Mar-88 09:05 PM

BX92:

READY

	AO	AP	AQ	AR	AS	BX	BY	BZ
73	Neut*Gam/Resist vs DENLOG							
74	Regression Output:							
75	Constant			103481.9				
76	Std Err of Y Est			12008.27				
77	R Squared			0.200291	R=0.45			
78	No. of Observations			105				
79	Degrees of Freedom			103				
80								
81	X Coefficient(s)	-37826.7						
82	Std Err of Coef.	7447.588						
83								
84								
85	Neut*Res/Gam vs DENLOG							
86	Regression Output:							
87	Constant			-4209.70				
88	Std Err of Y Est			512.3880				
89	R Squared			0.304848	R=0.55			
90	No. of Observations			105				
91	Degrees of Freedom			103				

23-Mar-88 09:05 PM

BX112:

READY

	HU	HI	HW	HN	HU	DA	DI	DL
73	X Coefficient(s)	2135.774						
94	Std Err of Coef.	317.7855						
95								
76								
77	Neutron vs Resist							
	Regression Output:							
	Constant	1769.041						
100	Std Err of Y Est	260.3475						
101	R Squared	0.612373	R=0.78					
102	No. of Observations	105						
103	Degrees of Freedom	103						
104								
105	X Coefficient(s)	30.85270						
106	Std Err of Coef.	2.418651						
107								
108								
109	Neutron vs log(Resist)							
110	Regression Output:							
111	Constant	813.3694						
112	Std Err of Y Est	257.7537						
113-Mar-88	09:06 PM							

BX132:

READY

	AD	AP	AQ	AR	AS	BX	BY	BZ
113	R Squared			0.620058	R=0.79			
114	No. of Observations			105				
115	Degrees of Freedom			103				
116								
117	X Coefficient(s)	1281.906						
118	Std Err of Coef.	98.87344						
119								
120								
121	log(Neutron) vs Resistivity							
122	Regression Output:							
123	Constant	3.258456						
124	Std Err of Y Est	0.051482						
125	R Squared	0.569790	R=0.75					
126	No. of Observations	105						
127	Degrees of Freedom	103						
128								
129	X Coefficient(s)	0.005586						
130	Std Err of Coef.	0.000478						
131								
132								
133-Mar-88	09:06 PM							

LW5:

READY

	AG	AH	AI	AJ	AK	BU	BV	BW
5	log[NEUTRON LOG] vs [DENSITY LOG]							
	Regression Output:							
8	Constant	2.423573						
9	Std Err of Y Est	0.042476						
10	R Squared	0.707138	R=0.84					
11	No. of Observations	105						
12	Degrees of Freedom	103						
13								
14	X Coefficient(s)	0.412457						

```

18          LOG10 LOG] vs [DENSITY LOG]
19      Regression Output:
20      Constant                403.4675
21      Std Err of Y Est        24.97695
22      R Squared                0.430050   R=0.656
23      No. of Observations      105
24      Degrees of Freedom        103
25-Mar-88  09:08 PM

```

BW25:

READY

```

25      AG      AH      AI      AJ      AK      BU      BV      BW
26      X Coefficient(s)  -136.563
27      Std Err of Coef.  15.49082
28
29
30      [SONIC LOG] vs [DENSITY LOG]
31      Regression Output:
32      Constant                1184.357
33      Std Err of Y Est        58.23878
34      R Squared                0.457960   R=0.677
35      No. of Observations      105
36      Degrees of Freedom        103
37
38      X Coefficient(s)  -336.949
39      Std Err of Coef.   36.11997
40
41
42      [RESISTIVITY] vs [DENSITY LOG]
43      Regression Output:
44      Constant                -56.1810
45-Mar-88  09:08 PM

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3W45:

READY

```

45      AG      AH      AI      AJ      AK      BU      BV      BW
46      Std Err of Y Est      9.253738
47      R Squared              0.238777   R=0.489
48      No. of Observations    105
49      Degrees of Freedom      103
50
51      X Coefficient(s)   32.62211
52      Std Err of Coef.    5.739212
53
54      [NEUTRON LOG] vs [DENSITY LOG]
55      Regression Output:
56      Constant             -2553.98
57      Std Err of Y Est      237.6640
58      R Squared              0.676976   R=0.823
59      No. of Observations    105
60      Degrees of Freedom      103
61
62      X Coefficient(s)   2165.644
63      Std Err of Coef.   147.4004
64-Mar-88  09:08 PM

```

4W65:

READY

log[SONIC] vs log[DENLOG]

Regression Output:

68 Constant 3.435219
69 Std Err of Y Est 0.061364
70 R Squared 0.467049 R=0.683
71 No. of Observations 105
72 Degrees of Freedom 103

74 X Coefficient(s) -0.36158
75 Std Err of Coef. 0.038058

log[RESIST] vs DENSITY LOG

Regression Output:

30 Constant -0.65685
31 Std Err of Y Est 0.222525
32 R Squared 0.249509 R=0.50
33 No. of Observations 105
34 Degrees of Freedom 103

23-Mar-88 09:08 PM

3W85:

READY

AG AH AI AJ AK BU BV BW

35
86 X Coefficient(s) 0.807614
37 Std Err of Coef. 0.138011
38
89
90 log[SONIC] vs log[DENLOG]
91 Regression Output:
92 Constant 3.239445
93 Std Err of Y Est 0.062888
94 R Squared 0.440263 R=0.664
95 No. of Observations 105
96 Degrees of Freedom 103

97
98 X Coefficient(s) -1.75881
99 Std Err of Coef. 0.195405

log[RESIST] vs log[DENLOG]

Regression Output:

104 Constant -0.20738

13-Mar-88 09:08 PM

RW105:

READY

AG AH AI AJ AK BU BV BW

105 Std Err of Y Est 0.225249
106 R Squared 0.231020 R=0.48
107 No. of Observations 105
108 Degrees of Freedom 103

110 X Coefficient(s) 3.893308
111 Std Err of Coef. 0.699894

SONIC vs log[DENLOG]

Regression Output:

115 Constant 1003.163
116 Std Err of Y Est 59.50431

120
121 X Coefficient(s) -1642.54
122 Std Err of Coef. 184.9846
123
124 RESIST vs log[DENLOG]
23-Mar-88 09:09 PM

W125:

READY

	AG	AH	AI	AJ	AK	BU	BV	BW
125	Regression Output:							
126	Constant			-38.0370				
127	Std Err of Y Est			9.360116				
128	R Squared			0.221175	R=0.47			
129	No. of Observations			105				
130	Degrees of Freedom			103				
131								
132	X Coefficient(s)	157.2957						
133	Std Err of Coef.	29.08369						
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23-Mar-88 09:09 PM								

READY

3C44:

READY

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1      I      J      K      L      M      AC      AD      AE
2
3      X Coefficient(s)  -56.9978
4      Std Err of Coef.  3.838993
5
6
7      [WC vs NEUTRON]
8      Regression Output:
9      Constant          58.65095
10     Std Err of Y Est   6.121070
11     R Squared          0.639177 , R = 0.80
12     No. of Observations 81
13     Degrees of Freedom  79
14
15     X Coefficient(s)  -0.01916
16     Std Err of Coef.  0.001619
17
18
19     [WC vs SONIC]
20     Regression Output:
21     Constant          -20.5822
22     Std Err of Y Est   7.631422
23     R Squared          0.439146 , R = 0.66
24
25 Feb-88 08:58 PM

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AC43:

READY

I	J	K	L	M	AC	AD	AE
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21-Feb-88 09:00 PM							

AC62:

READY

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21-Feb-88 09:00 PM							

AC90:

READY

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Degrees of Freedom

79

X Coefficient(s) -2.11861
Std Err of Coef. 0.135025

X

21-Feb-88 09:00 PM

AN6:

READY

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[Qu vs N*D]

8

Regression Output:

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Constant

-85.63

10

Std Err of Y Est

12.18

11

R Squared

0.61 , R = 0.78

12

No. of Obs

58.00

13

Degrees of Freedom

56.00

14

15

X Coefficient(s)

0.02

16

Std Err of Coef.

0.00

17

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19

Regression Output:

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Constant

-893.67

20-Feb-88 08:58 PM

CALC

AG10:

READY

AB AC AD AE AF AG

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7      log[Qu] vs log[Neut*Den]
8      Regression Output:
9      Constant                -28.20
10     Std Err of Y Est         0.45
11     R Squared                0.59 , R=0.77
12     No. of Observations      59.00
13     Degrees of Freedom       57.00
14
15     X Coefficient(s)         7.69
16     Std Err of Coef.        0.85
17
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6-Mar-88 11:33 PM

CALC

17:

READY

V W X Y Z AA AB

```

1      Qu vs Neutron LOG
2      Regression Output:
3
4
5 Constant                -79.82
6 Std Err of Y Est        14.31
7 R Squared               0.48 R=0.69
8 No. of Observations     59.00
9 Degrees of Freedom       57.00
10
11 X Coefficient(s)        0.04
12 Std Err of Coef.       0.01
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26 X Coefficient(s)        247.78
27

```

Qu vs log[Neutron Log]
Regression Output:

```

28 Constant                -827.17
29 Std Err of Y Est        13.93
30 R Squared               0.50 R=0.71
31 No. of Observations     59.00
32 Degrees of Freedom       57.00
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6-Mar-88 11:35 PM

CALC

127:

READY

V W X Y Z AA AB

```

107 Std Err of Coef.        32.63
108
109      log[Qu] vs log[Neutron Log]
110      Regression Output:
111
112 Constant                -27.82
113 Std Err of Y Est        0.51
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36						
37	X Coefficient(s)	8.41				3.7385
38	Std Err of Coef.	1.19				3.8203
39						3.7221
40						3.7356
41	log[Qu] vs Neutron*Density Log					3.7937
	Regression Output:					3.7663
42	Constant		-13.69			3.8681
43	Std Err of Y Est		0.37			3.7602
44	R Squared		0.72	R=0.85		3.8513
45	No. of Observations		59.00			3.7213
46	Degrees of Freedom		57.00			3.7690
16-Mar-88 11:35 PM						

CALC

Z47:

READY

	V	W	X	Y	Z	AA	AB
47							
48	X Coefficient(s)		6.21			3.8547	
49	Std Err of Coef.		0.51			3.7178	
50						3.8350	
51	log[Qu] vs log[Neutron*Density]					3.7417	
52						3.7221	
53						3.8532	
54						3.8783	
55						3.7802	
56						3.8079	
57						3.6690	
58						3.7626	
59						3.8543	
60						3.7503	
61						3.7269	
62						3.8131	
63						3.7174	
64						3.7054	
65						3.7125	
66							

16-Mar-88 11:36 PM

CALC

AI25:

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AI45:

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AI65:

READY

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Regression Output:

Constant 129.3878
Std Err of Y Est 96.57546
R Squared 0.000723 R=0.03
No. of Observations 52
Degrees of Freedom 50

X Coefficient(s) 0.617918
Std Err of Coef. 3.247476

27-Mar-88 05:33 PM

A025:

READY

V W X Y Z AA AB AO

PI vs GAMMA

Regression Output:

Constant -53.8494
Std Err of Y Est 82.71658
R Squared 0.151419 R=0.39
No. of Observations 52
Degrees of Freedom 50

X Coefficient(s) 1.321505
Std Err of Coef. 0.442425

PI vs DenLog

Regression Output:

Constant 886.3669
Std Err of Y Est 73.56343
R Squared 0.328830 R=0.57
No. of Observations 52
Degrees of Freedom 50

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A045:

READY

V W X Y Z AA AB AO

X Coefficient(s) -365.526
Std Err of Coef. 73.85231

PI vs NEUTRON

Regression Output:

Constant 349.7601
Std Err of Y Est 86.25874
R Squared 0.077186 R=0.28
No. of Observations 52
Degrees of Freedom 50

X Coefficient(s) -0.12382
Std Err of Coef. 0.060548

LL vs DenLog/GAMMA

Regression Output:

Constant 294.0664
Std Err of Y Est 86.48093

V	W	X	Y	Z	AA	AB	AO
46	R Squared			0.198704	R=0.45		
47	No. of Observations			52			
48	Degrees of Freedom			50			
51	X Coefficient(s)	-8591.57					
52	Std Err of Coef.	2439.946					
53							
54	LL vs DenLog*GAMMA						
55	Regression Output:						
56	Constant			7.105132			
57	Std Err of Y Est			93.53256			
58	R Squared			0.062701	R=0.25		
59	No. of Observations			52			
60	Degrees of Freedom			50			
62	X Coefficient(s)	0.497685					
63	Std Err of Coef.	0.272125					

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AI26:

READY

AB	AC	AD	AE	AF	AG	AH	AI
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AI46:

READY

AB	AC	AD	AE	AF	AG	AH	AI
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X Coefficient(s) -1.00865
Std Err of Coef. 0.199934

log[LL] vs log[DENLOG]
Regression Output:

Constant 3.652961
Std Err of Y Est 0.198568

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AI66:

READY

AB	AC	AD	AE	AF	AG	AH	AI
47	R Squared			0.341199	R=0.58		
48	No. of Observations			52			
49	Degrees of Freedom			50			
51	X Coefficient(s)	-4.86842					
52	Std Err of Coef.	0.956702					

log[LL] vs log[NEUTRON]
Regression Output:

Constant 8.770699
Std Err of Y Est 0.227268
R Squared 0.137002 R=0.37
No. of Observations 52
Degrees of Freedom 50

X Coefficient(s) -2.04080
Std Err of Coef. 0.724364

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AI86:

READY

AB	AC	AD	AE	AF	AG	AH	AI
57	LL vs log[NEUTRON]						
58	Regression Output:						
69	Constant			2300.727			
70	Std Err of Y Est			92.08967			
71	R Squared			0.091397	R=0.30		
72	No. of Observations			52			
73	Degrees of Freedom			50			
75	X Coefficient(s)	-658.256					
76	Std Err of Coef.	293.5147					

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LL vs log(DENLOG)
Regression Output:

Constant	779.7527
Std Err of Y Est	77.45903
R Squared	0.357169 R=0.60
No. of Observations	52
Degrees of Freedom	50
X Coefficient(s)	-1967.03
Std Err of Coef.	373.1971

LL vs log(GAMMA)

Regression Output:

Constant	-686.797
Std Err of Y Est	88.51227
R Squared	0.160619 R=0.40
No. of Observations	52
Degrees of Freedom	50

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A045:

READY

	AH	AI	AJ	AK	AL	AM	AN	AO
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PI vs log(DENLOG)
Regression Output:

Constant	693.1834
Std Err of Y Est	72.86407
R Squared	0.341531 R=0.58
No. of Observations	52
Degrees of Freedom	50

X Coefficient(s)	-1787.77
Std Err of Coef.	351.0585

PI vs log(NEUTRON)
Regression Output:

Constant	1914.267
----------	----------

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.065:

READY

	AH	AI	AJ	AK	AL	AM	AN	AO
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X Coefficient(s)	-549.286
Std Err of Coef.	275.4530

PI vs log(GAMMA)

48 NO. OF OBSERVATIONS
 49 Degrees of Freedom 50
 50 X Coefficient(s) -626.337
 51 Std Err of Coef. 176.7714
 52
 53 LL vs DenLog*neut/Gamma
 54 Regression Output:
 55 Constant 245.1507
 56 Std Err of Y Est 87.79723
 57 R Squared 0.174126 R=0.42
 58 No. of Observations 52
 59 Degrees of Freedom 50
 60
 61 X Coefficient(s) -2.97014
 62 Std Err of Coef. 0.914781
 63
 64
 65

27-Mar-88 05:40 PM

U25: READY

66 AY AZ BA BB BC BD BU BV
 67 LL vs Den*Gamma/Neut
 68 Regression Output:
 69 Constant 25.83007
 70 Std Err of Y Est 92.54563
 71 R Squared 0.082377 R=0.29
 72 No. of Observations 52
 73 Degrees of Freedom 50
 74
 75 X Coefficient(s) 814.6648
 76 Std Err of Coef. 384.5215
 77
 78

79 LL vs (D*N*R/S*G)
 80 Regression Output:
 81 Constant 173.2970
 82 Std Err of Y Est 92.69352
 83 R Squared 0.079442 R=0.28
 84 No. of Observations 52
 85 Degrees of Freedom 50
 86

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BU45: READY

87 AY AZ BA BB BC BD BU BV
 88 X Coefficient(s) -43.9885
 89 Std Err of Coef. 21.17643
 90
 91 LL vs D*N*R/G
 92 Regression Output:
 93 Constant 179.4970
 94 Std Err of Y Est 92.28702
 95 R Squared 0.087499 R=0.30
 96 No. of Observations 52
 97 Degrees of Freedom 50
 98

65:

	AY	AZ	BA	BB	BC	BD	BU	BV
16		R Squared			0.035680	R=0.19		
17		No. of Observations			52			
48		Degrees of Freedom			50			
19								
30		X Coefficient(s)	-0.00092					
51		Std Err of Coef.	0.000682					
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مذہب:

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      BJ          BK          BL          BM          BN          BP          BQ          BR
6      LL vs Gamma/DenLog
      Regression Output:
-      Constant          -57.5093
9      Std Err of Y Est      82.07925
0      R Squared          0.278196 R=0.53
1      No. of Observations      52
12     Degrees of Freedom      50
13
14     X Coefficient(s)  3.327310
15     Std Err of Coef.  0.757952
16
17
18     LL vs Gamma/D*N
19     Regression Output:
20     Constant          0.601969
21     Std Err of Y Est      84.80868
22     R Squared          0.229393 R=0.48
23     No. of Observations      52
24     Degrees of Freedom      50
25
27-Mar-88  05:43 PM

```

15

READY

	BJ	BK	BL	BM	BN	BP	BQ	BR
29. X Coefficient(s)			4414.679					

APPENDIX IV

GEOTECHNICAL OIL SANDS CORRELATIONS

Regression Analysis Output for
Moisture Content (%) vs Bulk Density Log

Regression Output:

Constant	156.8910		
Std Err of Y Est	5.349495		
R Squared	0.591290	R Value	0.768954
No. of Observations	159		
Degrees of Freedom	157		

X Coefficient(s) -64.8761
Std Err of Coef. 4.304689

$$Y = -64.876X + 156.891$$

Regression Analysis Output for
Log of Moisture Content (Log %) vs Bulk Density Log

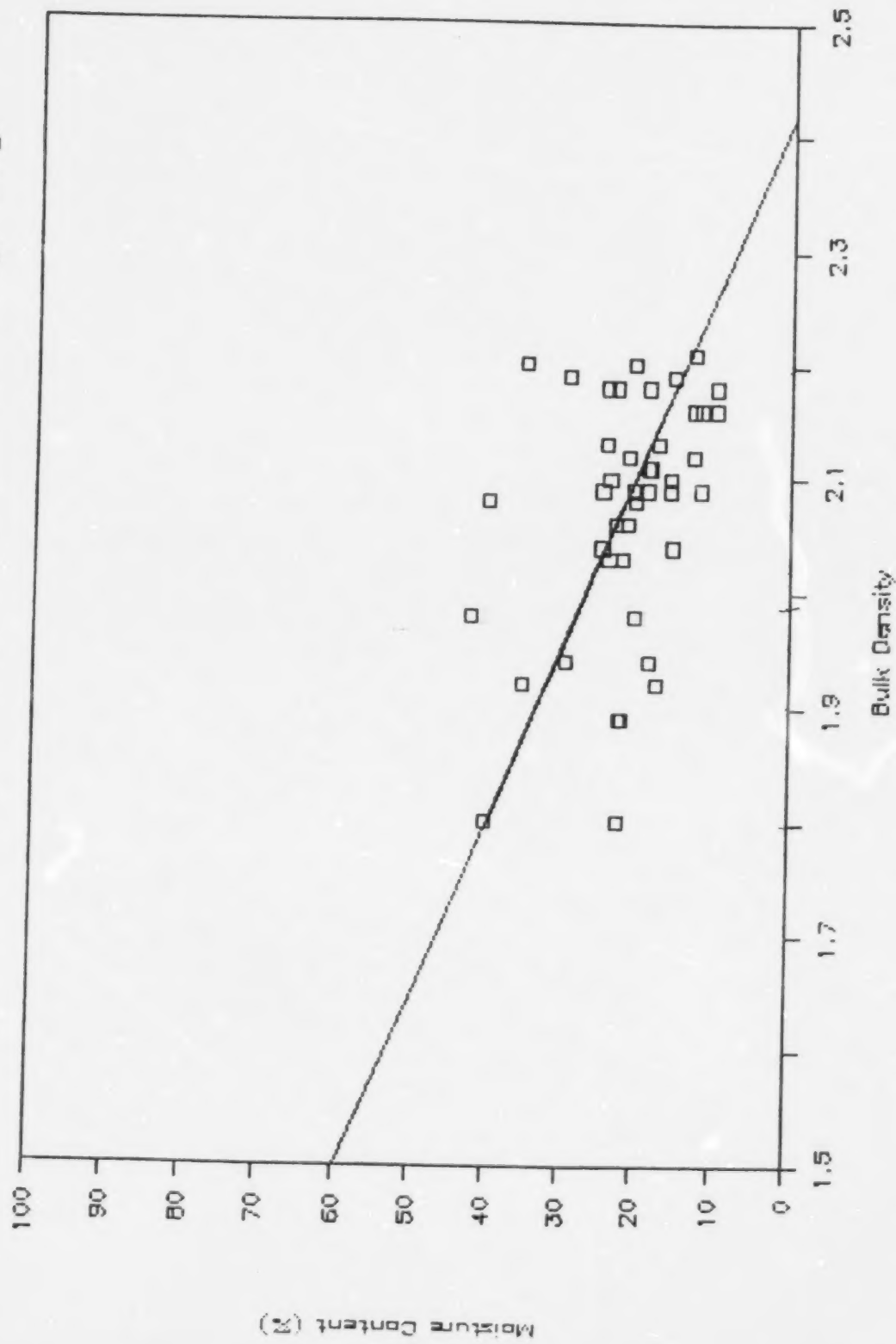
Regression Output:

Constant	3.790103		
Std Err of Y Est	0.100344		
R Squared	0.580499	R Value	0.761905
No. of Observations	159		
Degrees of Freedom	157		

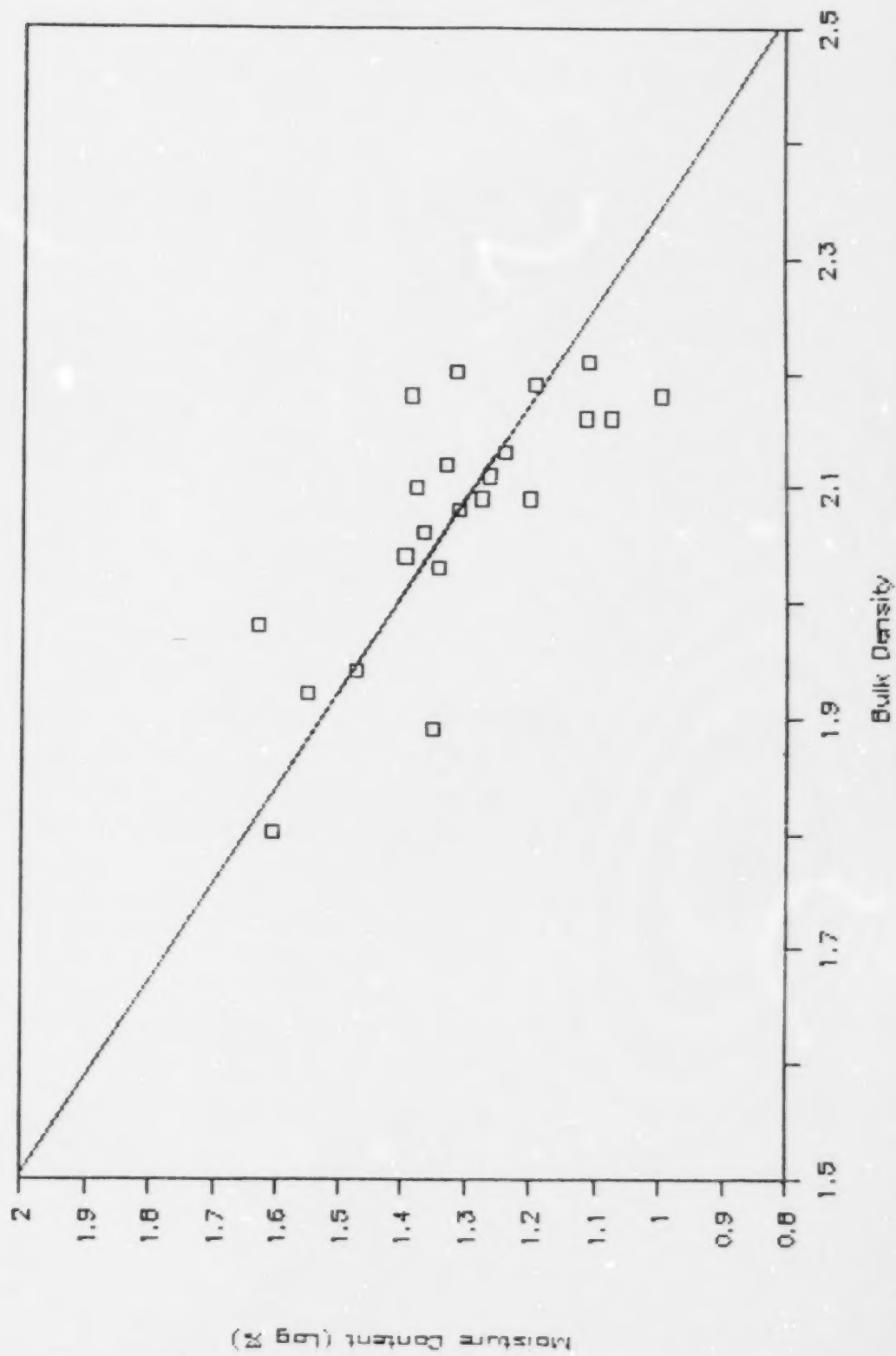
X Coefficient(s) -1.19016
Std Err of Coef. 0.080746

$$Y = -1.190X + 3.790$$

Moisture Content(%) vs Bulk Density Log



Log Water Content vs Bulk Density Log



X

Regression Analysis Output for
Moisture Content (%) vs Neutron Porosity Log

Regression Output:

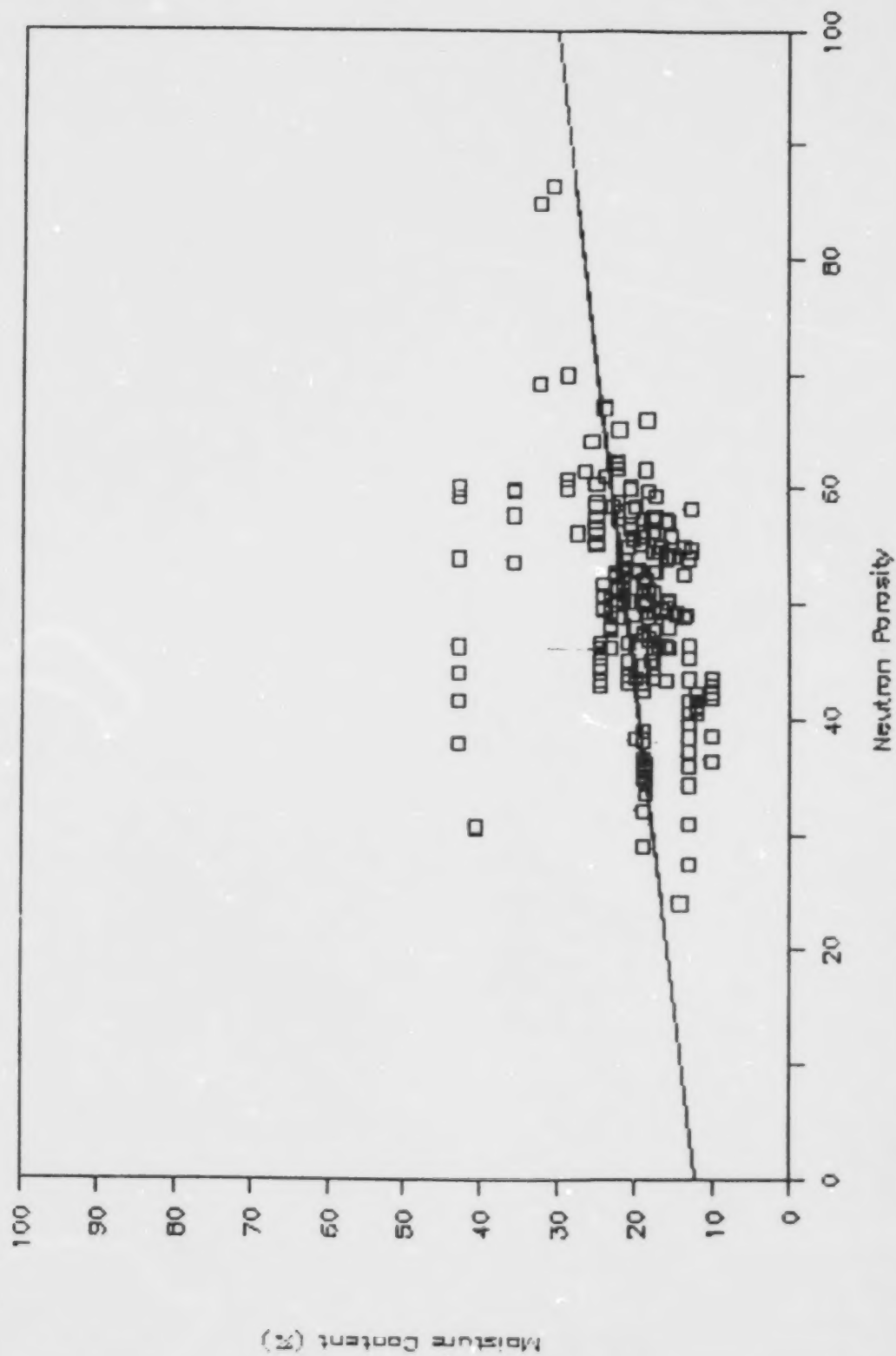
Constant	12.26879	
Std Err of Y Est	7.199949	
R Squared	0.053313	R Value 0.230896
No. of Observations	229	
Degrees of Freedom	227	
X Coefficient(s)	0.179679	
Std Err of Coef.	0.050254	Y=0.180*X+12.269

Regression Analysis Output for
Log of Moisture Content (Log %) vs Neutron Porosity Log

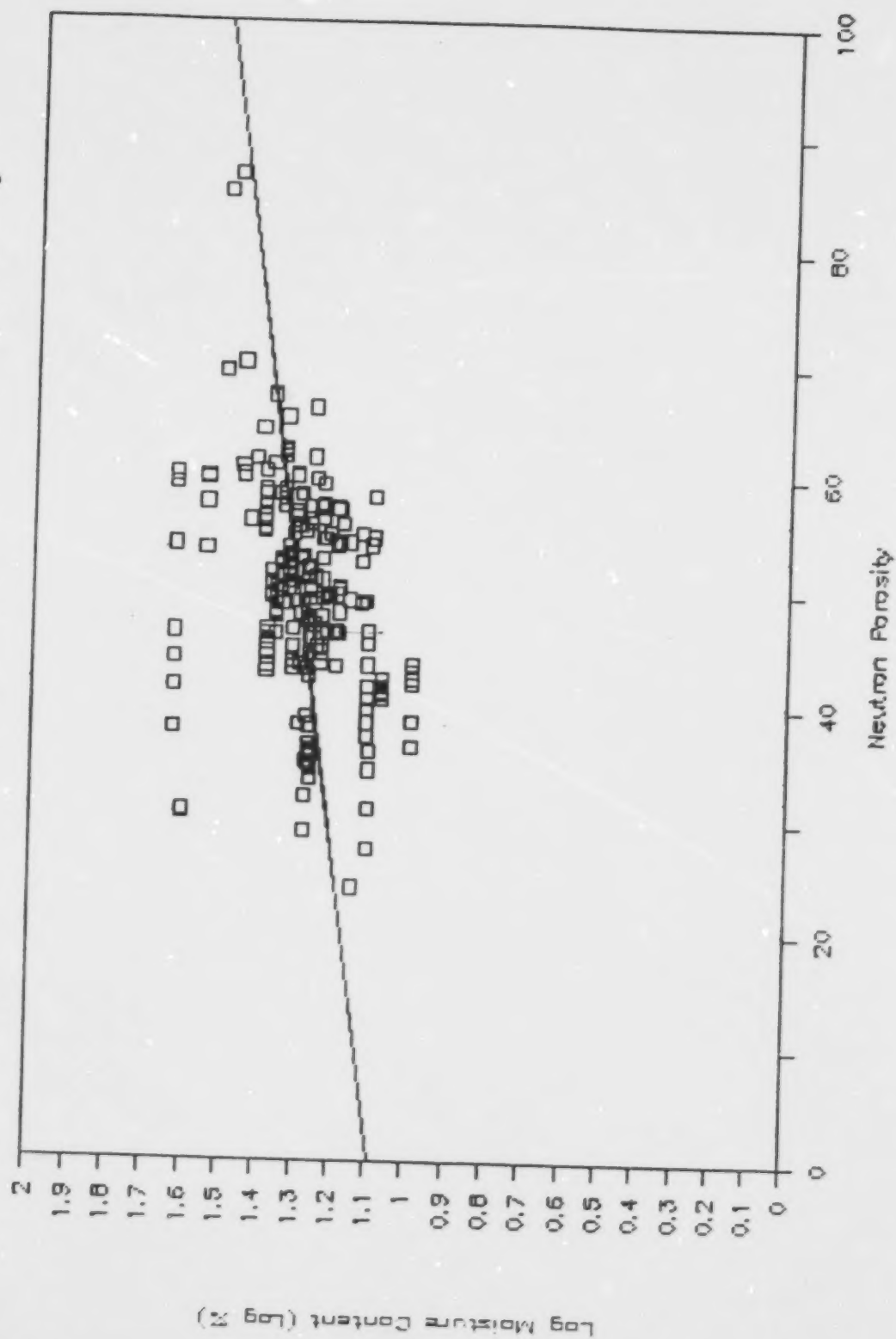
Regression Output:

Constant	1.087054	
Std Err of Y Est	0.131847	
R Squared	0.089626	R Value 0.299377
No. of Observations	229	
Degrees of Freedom	227	
X Coefficient(s)	0.004350	
Std Err of Coef.	0.000920	Y=0.004*X+1.087

Moisture Content(%) vs Neutron Porosity



Log M.C. (Log %) vs Neutron Porosity



Regression Analysis Output for
Undrained Shear Strength vs Bulk Density Log

Regression Output:

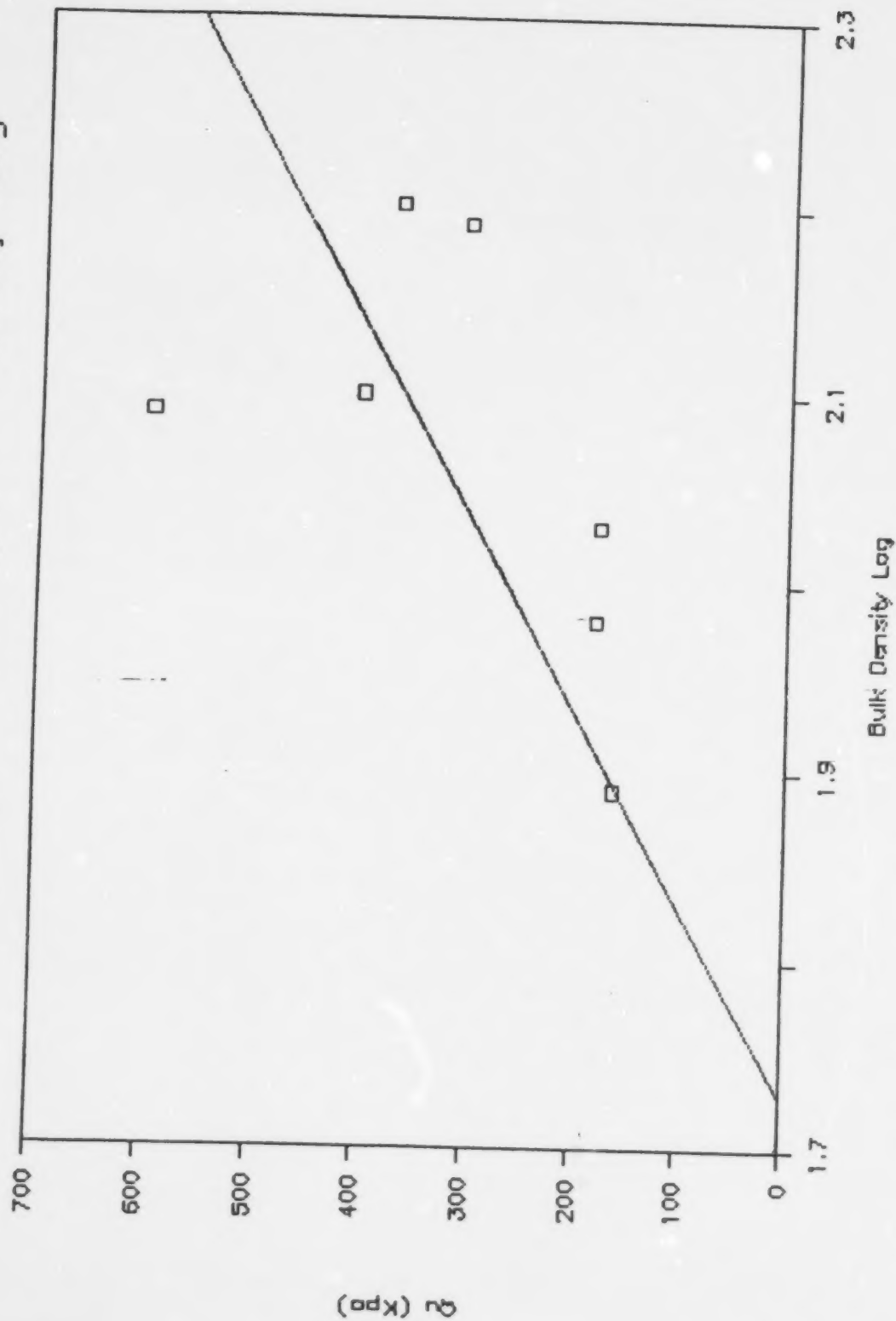
Constant	-1694.23		
Std Err of Y Est	135.1809		
R Squared	0.346617	R Value	0.589
No. of Observations	41		
Degrees of Freedom	39		
X Coefficient(s)	980.3771		
Std Err of Coef.	215.5359		$Y=980.377X-1694.23$

Regression Analysis Output for
Log of Undrained Shear Strength vs Bulk Density Log

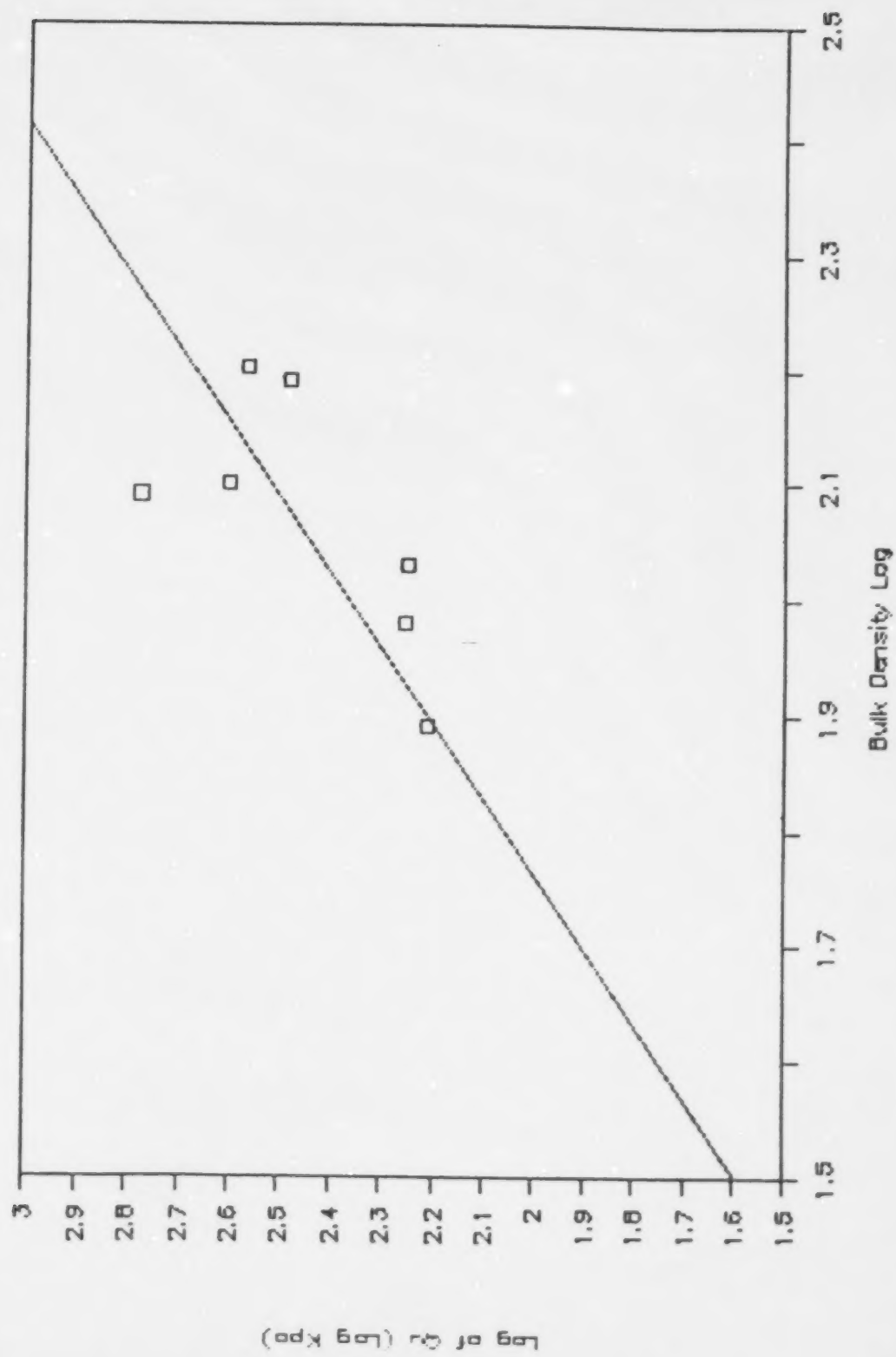
Regression Output:

Constant	-0.72090		
Std Err of Y Est	0.159056		
R Squared	0.487176	R Value	0.697980
No. of Observations	41		
Degrees of Freedom	39		
X Coefficient(s)	1.543640		
Std Err of Coef.	0.253603		$Y=1.544X-0.721$

Undrained Shear Strength vs Density Log



Log Of Shear Strength vs Density Log



Regression Analysis Output for
Liquid Limit vs Gamma Log

Regression Output:

Constant	96.70594	
Std Err of Y Est	42.77694	
R Squared	0.000754	R Value 0.027
No. of Observations	222	
Degrees of Freedom	220	

X Coefficient(s) 0.046645
Std Err of Coef. 0.114418

$$Y = 0.047 * X + 96.706$$

Regression Analysis Output for
Log of Liquid Limit vs Gamma Log

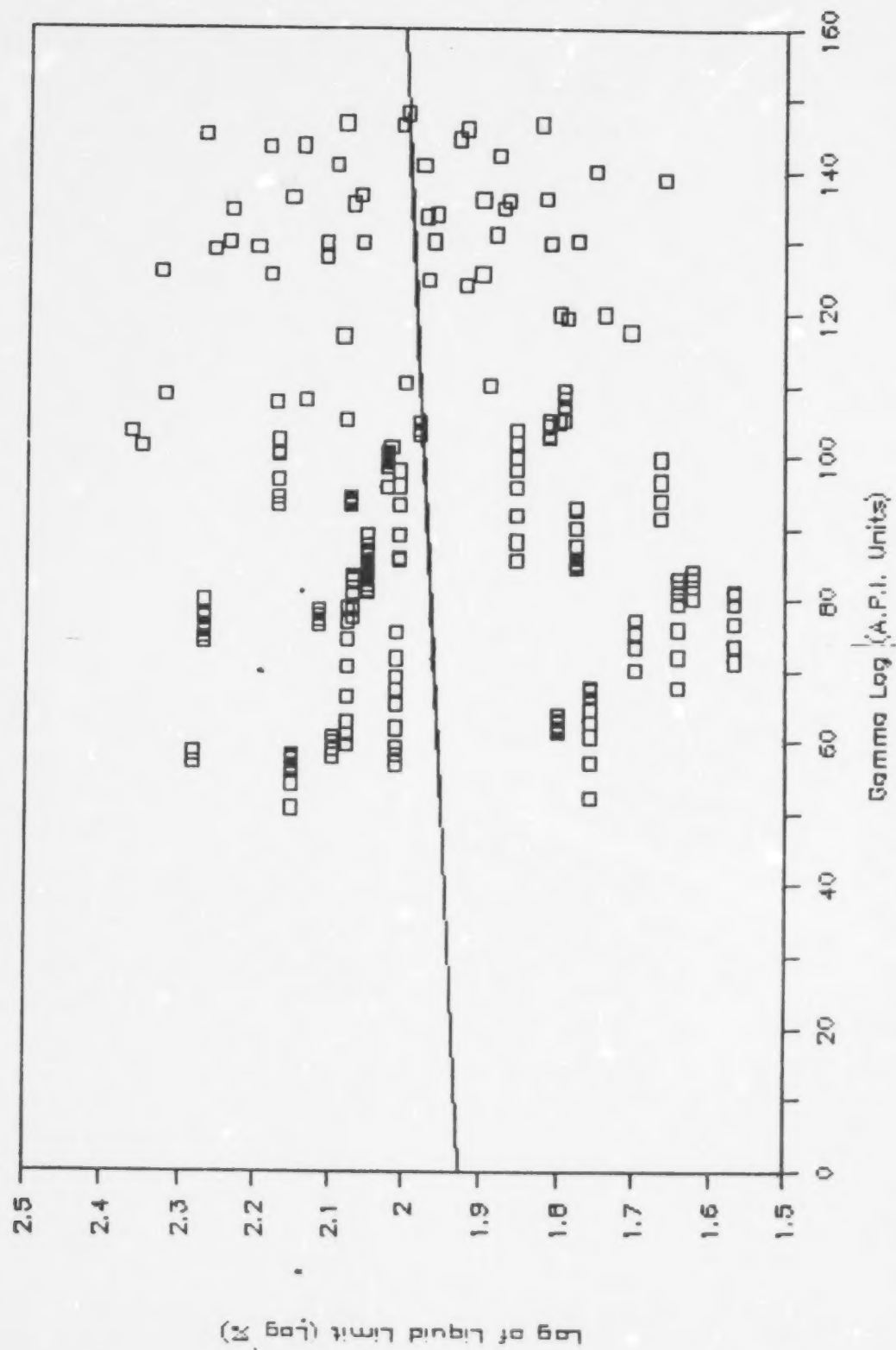
Regression Output:

Constant	1.926361	
Std Err of Y Est	0.194219	
R Squared	0.002710	R Value 0.052061
No. of Observations	222	
Degrees of Freedom	220	

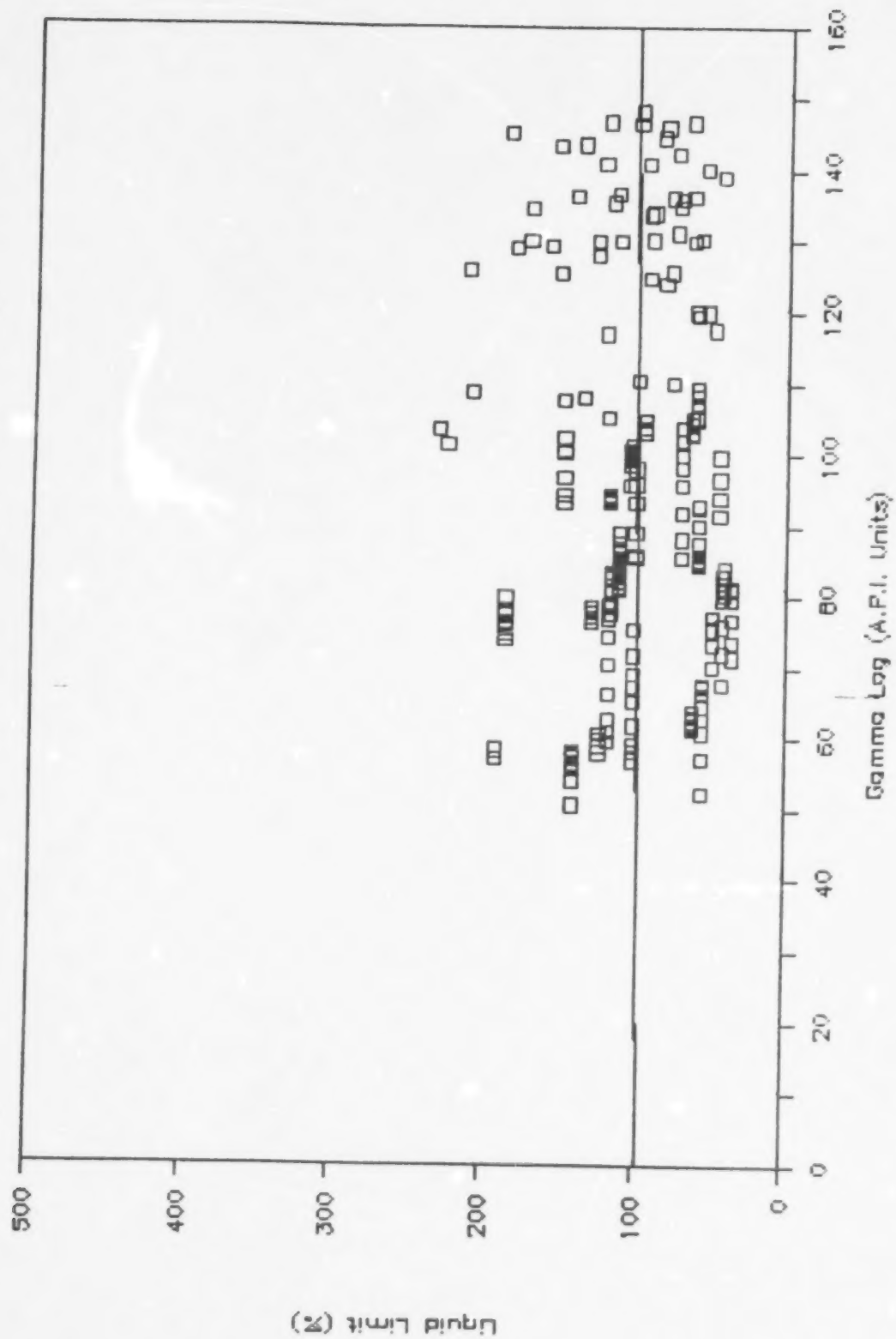
X Coefficient(s) 0.000401
Std Err of Coef. 0.000519

$$Y = 0.0004 * X + 1.926$$

Log of Liquid Limit vs Gamma Log



Liquid Limit vs Gamma Log



Regression Analysis Output for
Liquid Limit vs Bulk Density Log

Regression Output:

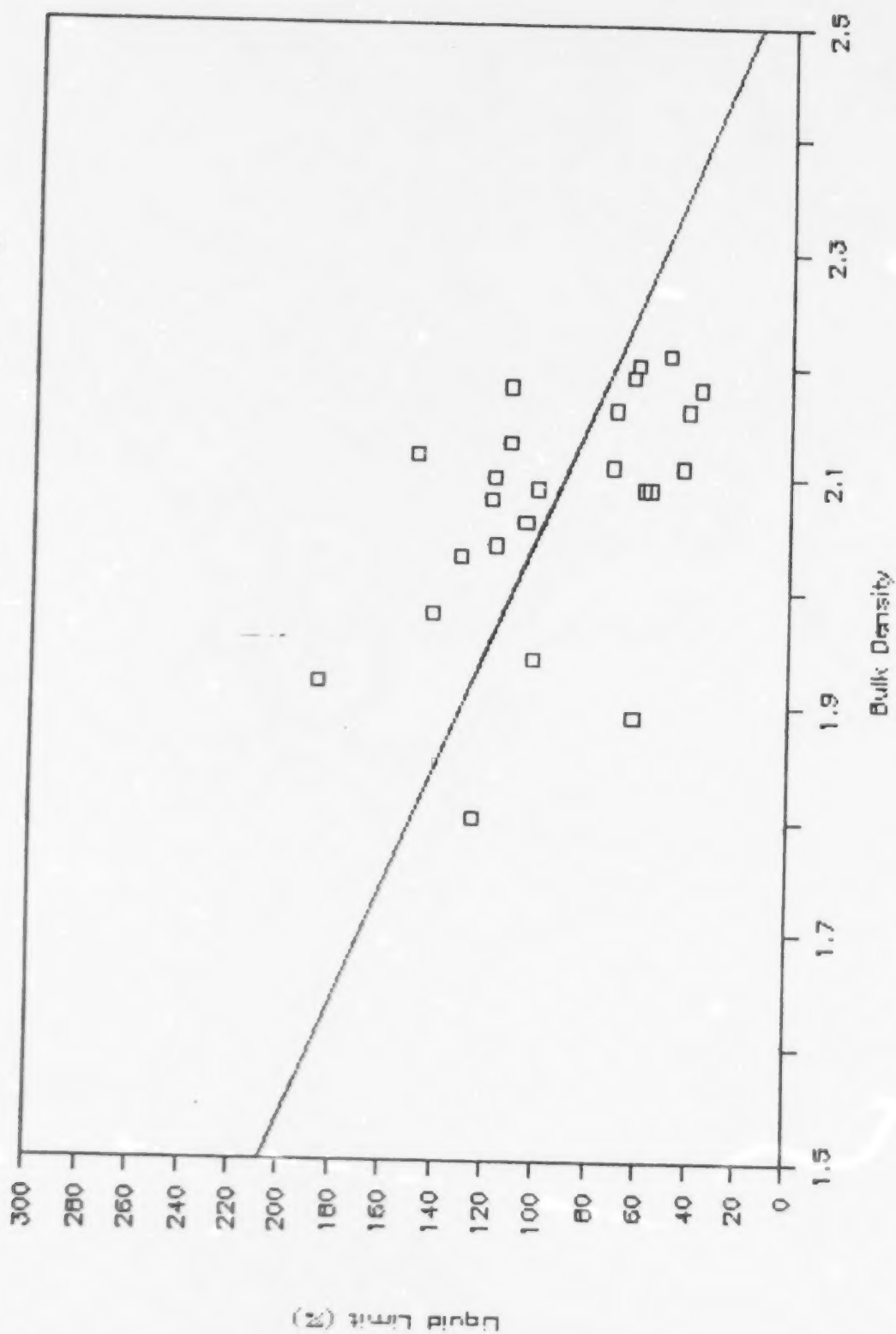
Constant	498.2389	
Std Err of Y Est	34.33036	
R Squared	0.235590	R Value 0.485376
No. of Observations	162	
Degrees of Freedom	160	
X Coefficient(s)	-193.705	
Std Err of Coef.	27.58459	Y=-193.705*X+498.239

Regression Analysis Output for
Log of Liquid Limit vs Bulk Density Log

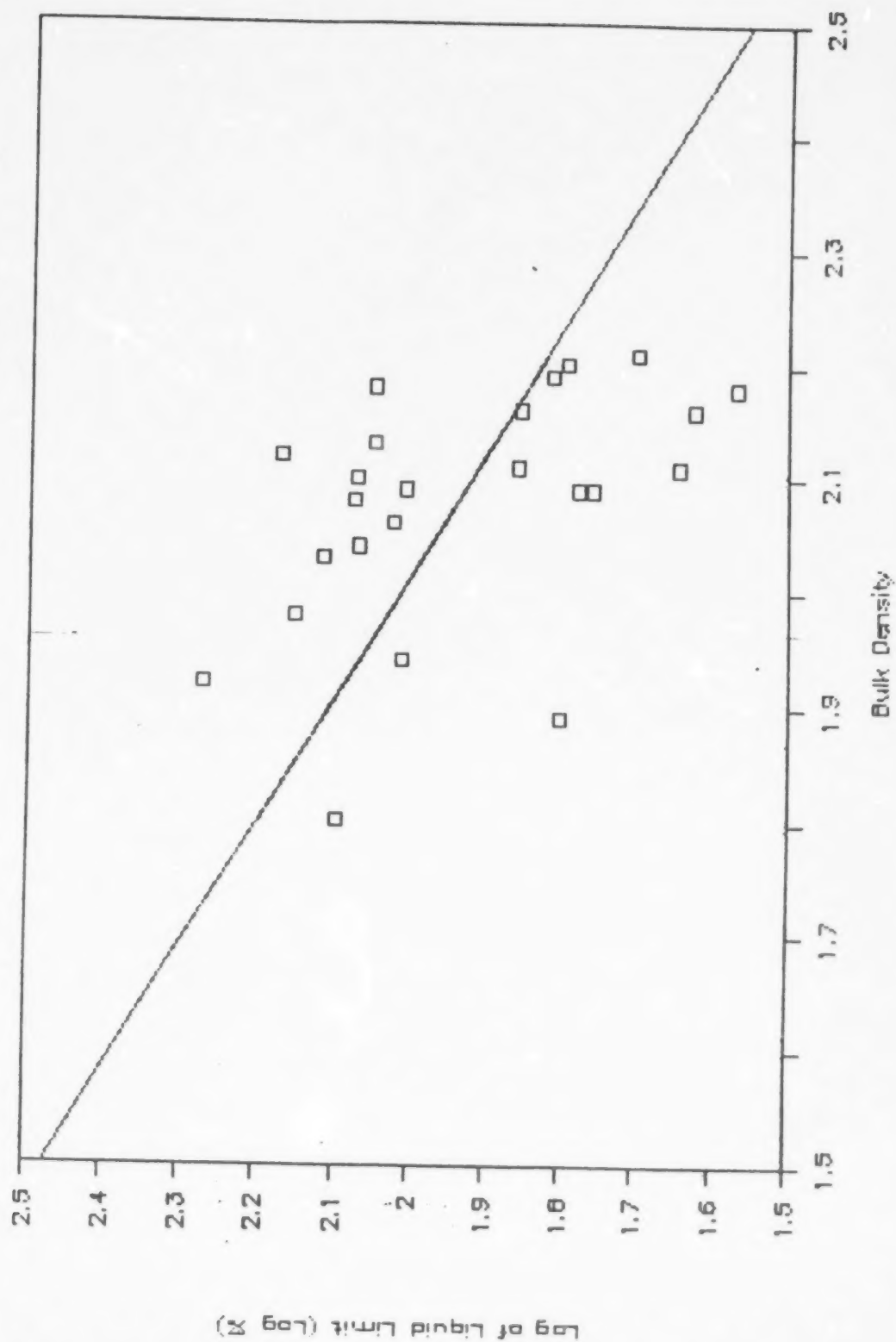
Regression Output:

Constant	3.858092	
Std Err of Y Est	0.169406	
R Squared	0.222968	R Value 0.472195
No. of Observations	162	
Degrees of Freedom	160	
X Coefficient(s)	-0.92231	
Std Err of Coef.	0.136118	Y=-0.922*X+3.858

Liquid Limit vs Bulk Density Log



Log Of Liquid Limit vs Bulk Density Log



Regression Analysis Output for
Plasticity Index vs Gamma Log

Strat.
Unit

Kcw

Regression Output:

Constant -21.7798
Std Err of Y Est 10.22038
R Squared 0.491905
No. of Observations 33
Degrees of Freedom 31

R Value 0.701359

X Coefficient(s) 0.666664
Std Err of Coef. 0.121690

$Y = 0.667 * X - 21.780$

Kca

Regression Output:

Constant 58.60003
Std Err of Y Est 20.97062
R Squared 0.124522
No. of Observations 59
Degrees of Freedom 57

R Value 0.352877

X Coefficient(s) 0.376026
Std Err of Coef. 0.132062

$Y = 0.376 * X + 58.600$

Kcb

Regression Output:

Constant 75.21050
Std Err of Y Est 41.78179
R Squared 0.016346
No. of Observations 82
Degrees of Freedom 80

R Value 0.127854

X Coefficient(s) 0.248868
Std Err of Coef. 0.215838

$Y = 0.249 * X + 75.211$

Kcc

Regression Output:

Constant -6.55463
Std Err of Y Est 23.71675
R Squared 0.199423
No. of Observations 68
Degrees of Freedom 66

R Value 0.446568

X Coefficient(s) 0.491663
Std Err of Coef. 0.121257

$Y = 0.492 * X - 6.555$

Regression Analysis Output for
Log of Plasticity Index vs Gamma Log

Strat.
Unit

Kcw

Regression Output:

Constant 0.857887
Std Err of Y Est 0.115940
R Squared 0.502732
No. of Observations 33
Degrees of Freedom 31

R Value 0.709036

X Coefficient(s) 0.007728
Std Err of Coef. 0.001380

$Y = 0.008 * X + 0.858$

Kca

Regression Output:

Constant 1.834886
Std Err of Y Est 0.101731
R Squared 0.070840
No. of Observations 59
Degrees of Freedom 57

R Value 0.266158

X Coefficient(s) 0.001335
Std Err of Coef. 0.000640

$Y = 0.001 * X + 1.835$

Kcb

Regression Output:

Constant 1.845154
Std Err of Y Est 0.209151
R Squared 0.012491
No. of Observations 82
Degrees of Freedom 80

R Value 0.111767

X Coefficient(s) 0.001086
Std Err of Coef. 0.001080

$Y = 0.001 * X + 1.845$

Kcc

Regression Output:

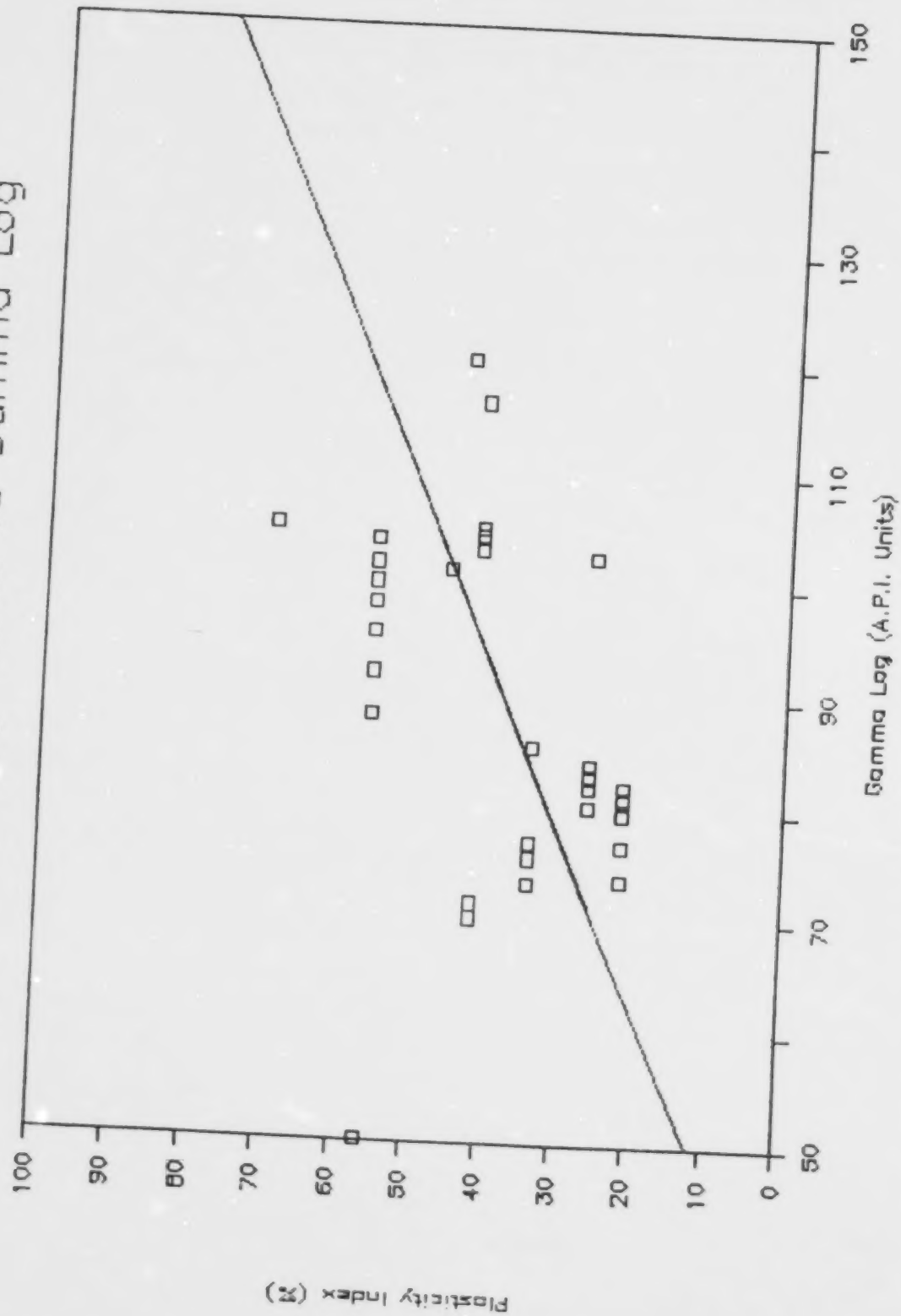
Constant 1.166412
Std Err of Y Est 0.181695
R Squared 0.236108
No. of Observations 68
Degrees of Freedom 66

R Value 0.485909

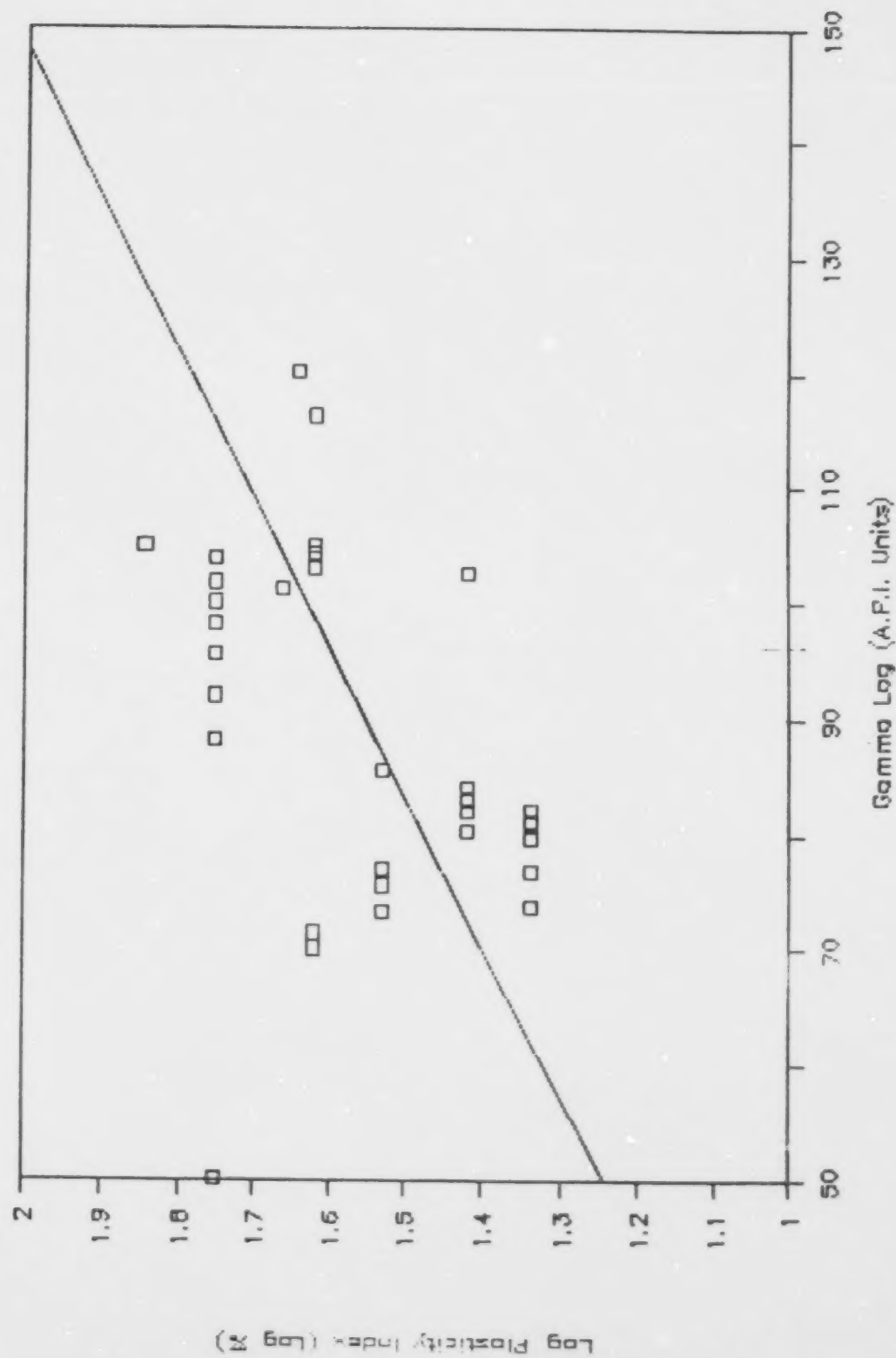
X Coefficient(s) 0.004195
Std Err of Coef. 0.000928

$Y = 0.004 * X + 1.166$

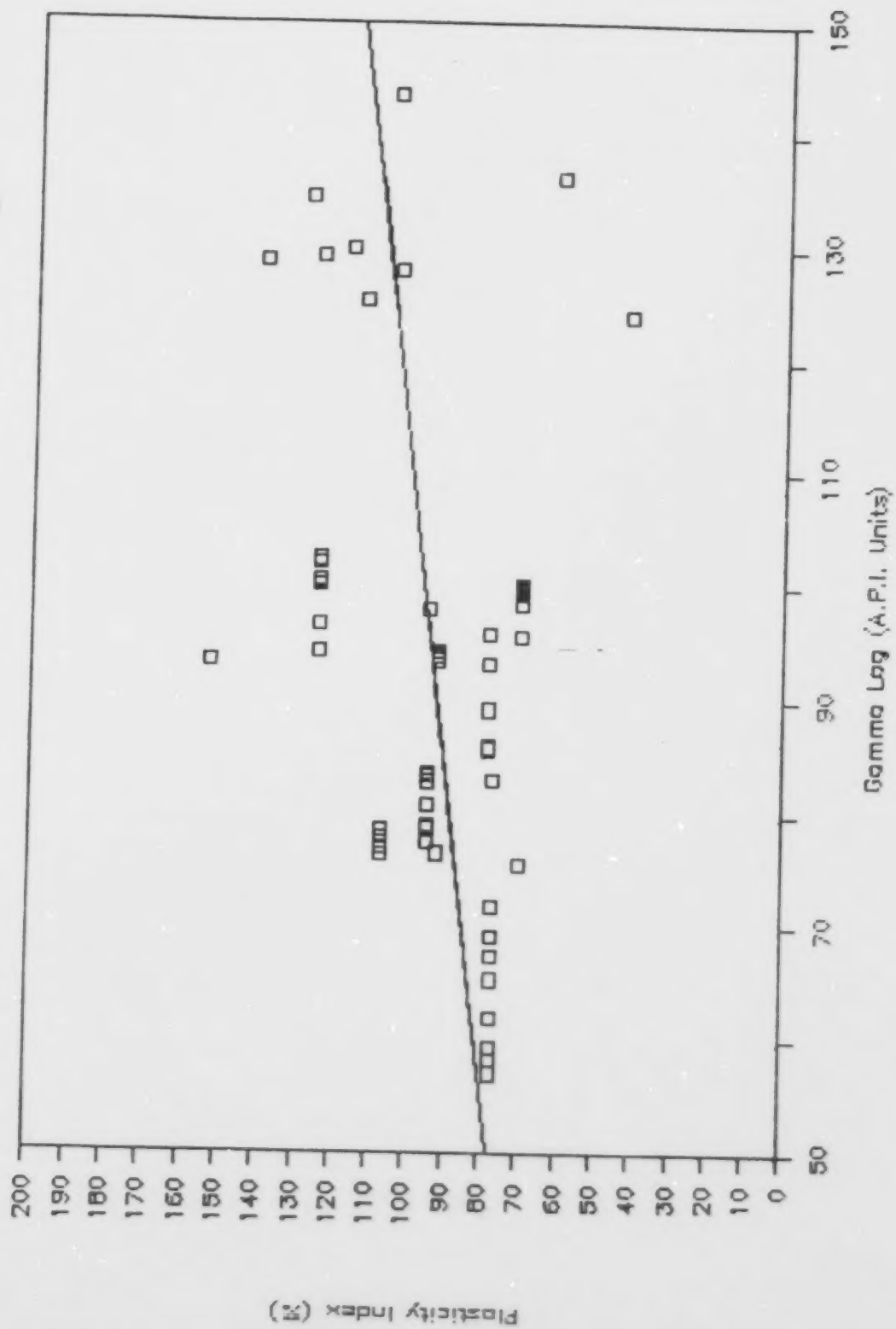
K_{cw} Plasticity Index vs Gamma Log



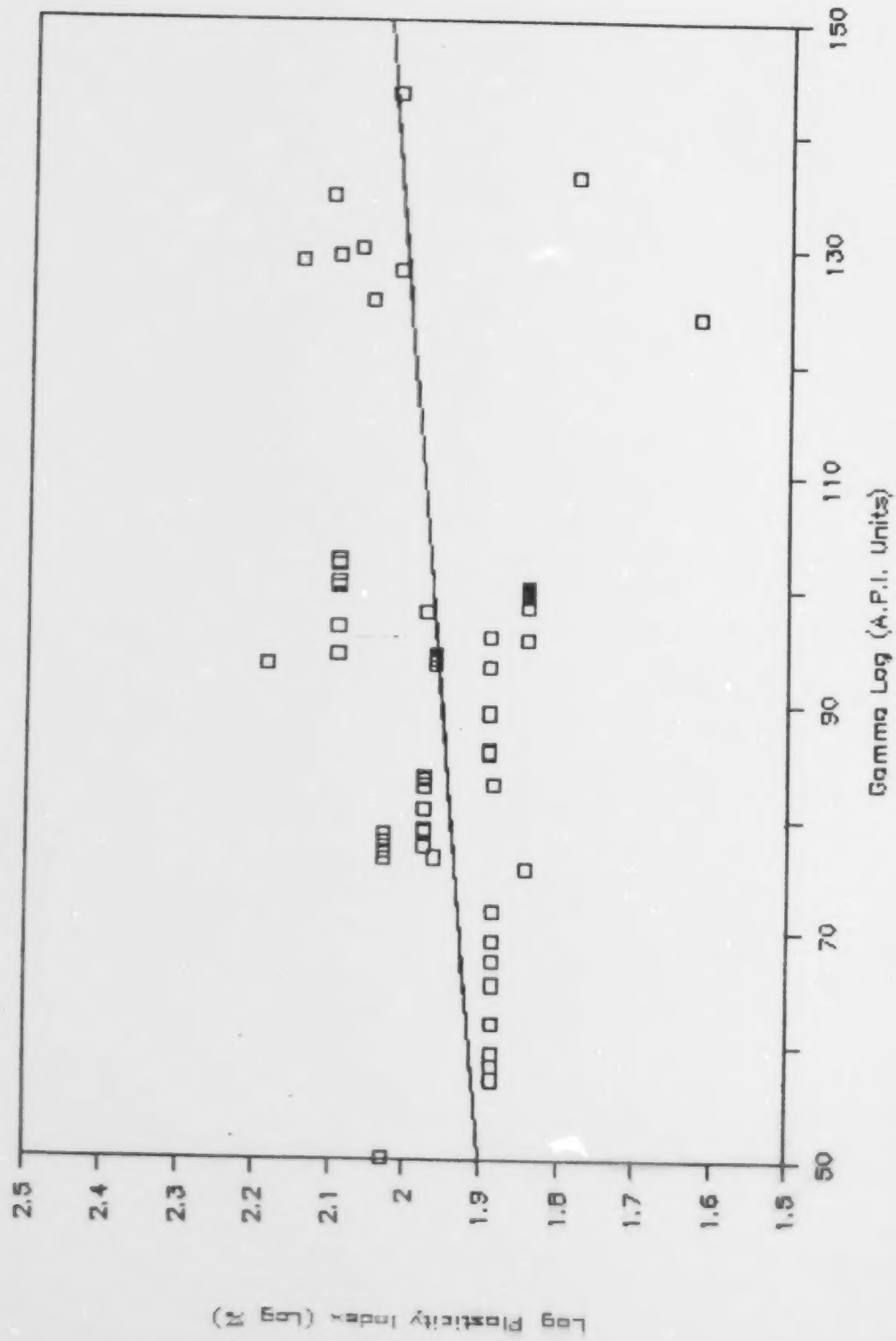
Log Kew Plasticity Index vs Gamma Log



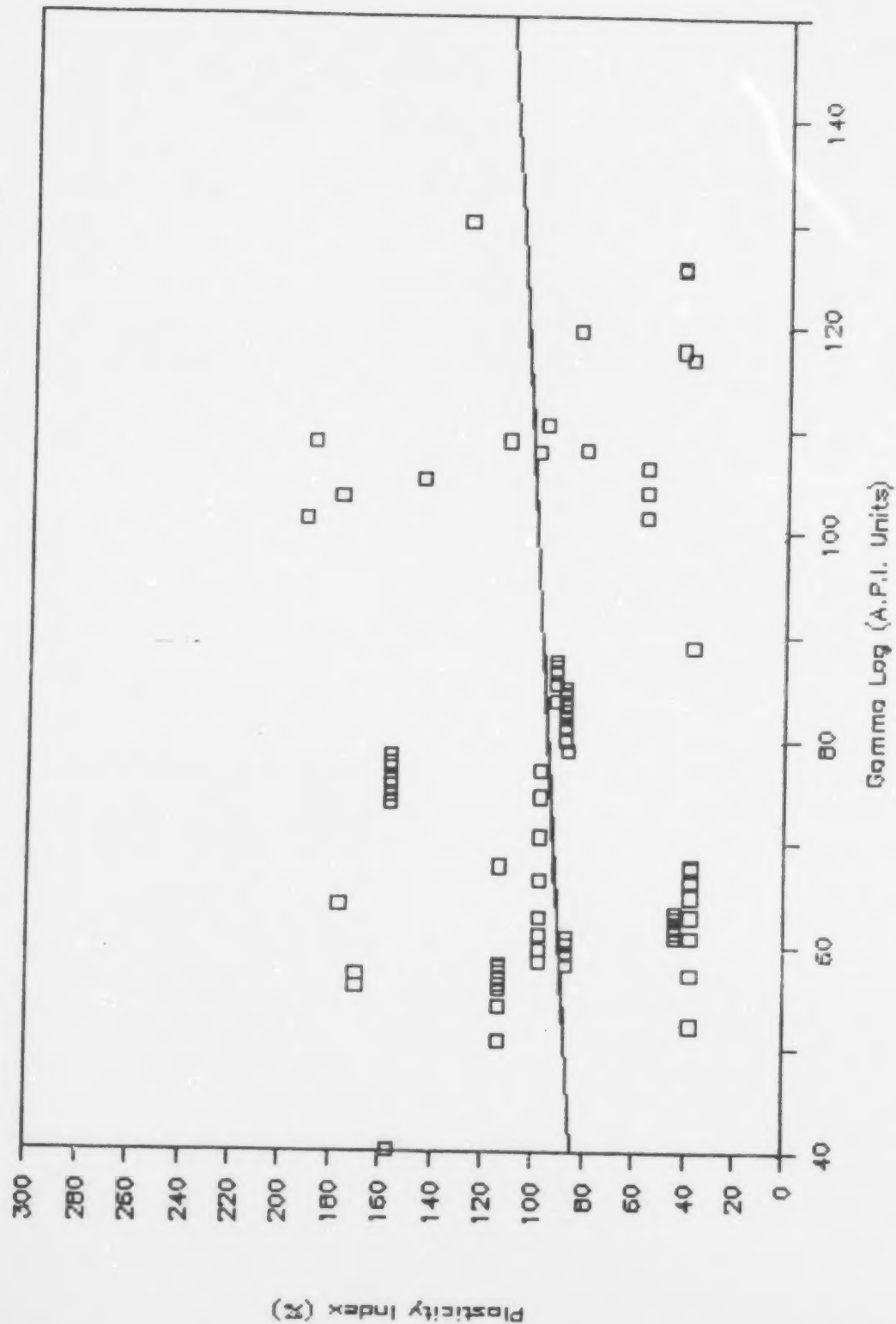
Kca Plasticity Index vs Gamma Log



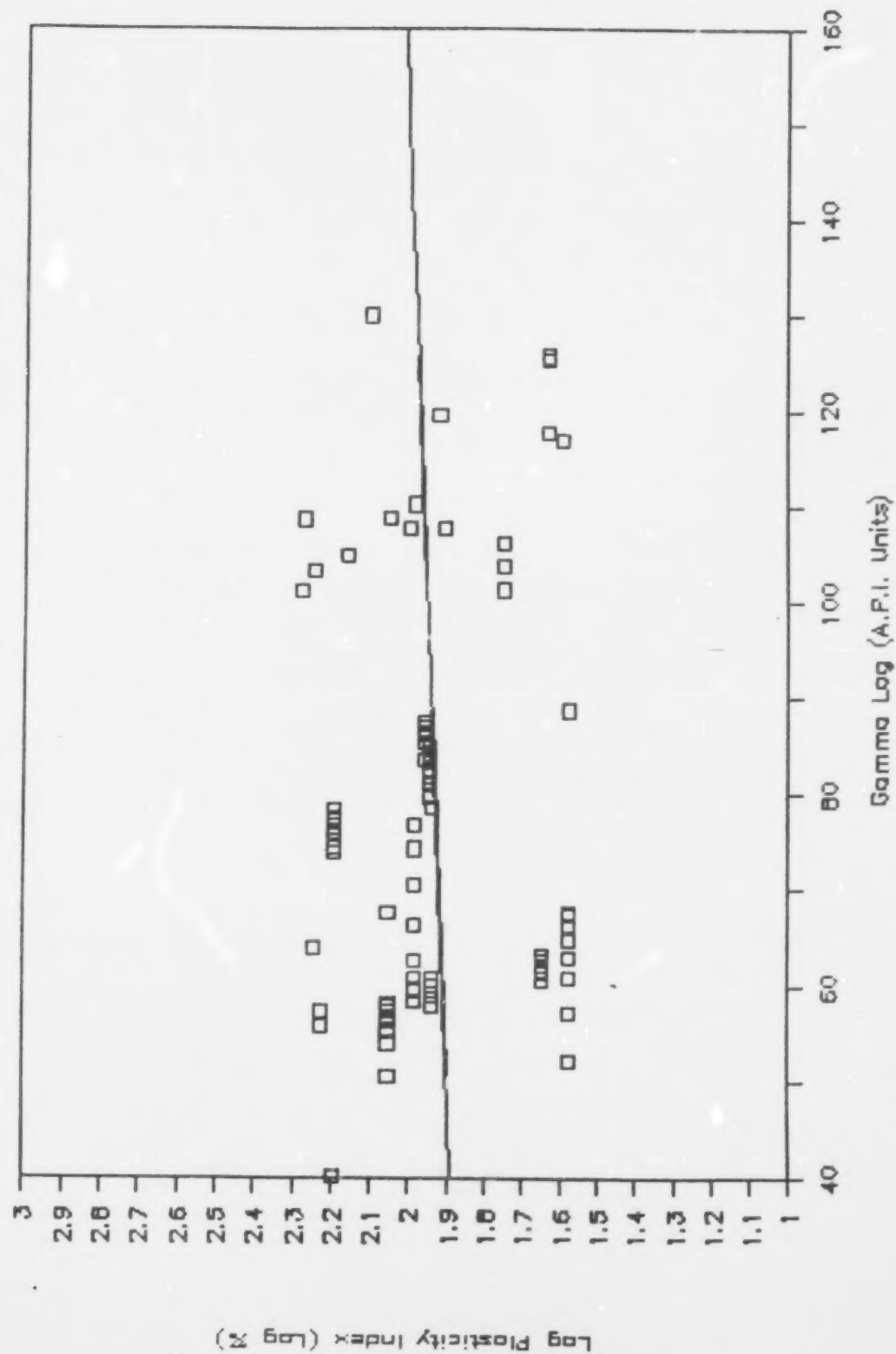
Log K_{ea} Plasticity Index vs Gamma Log



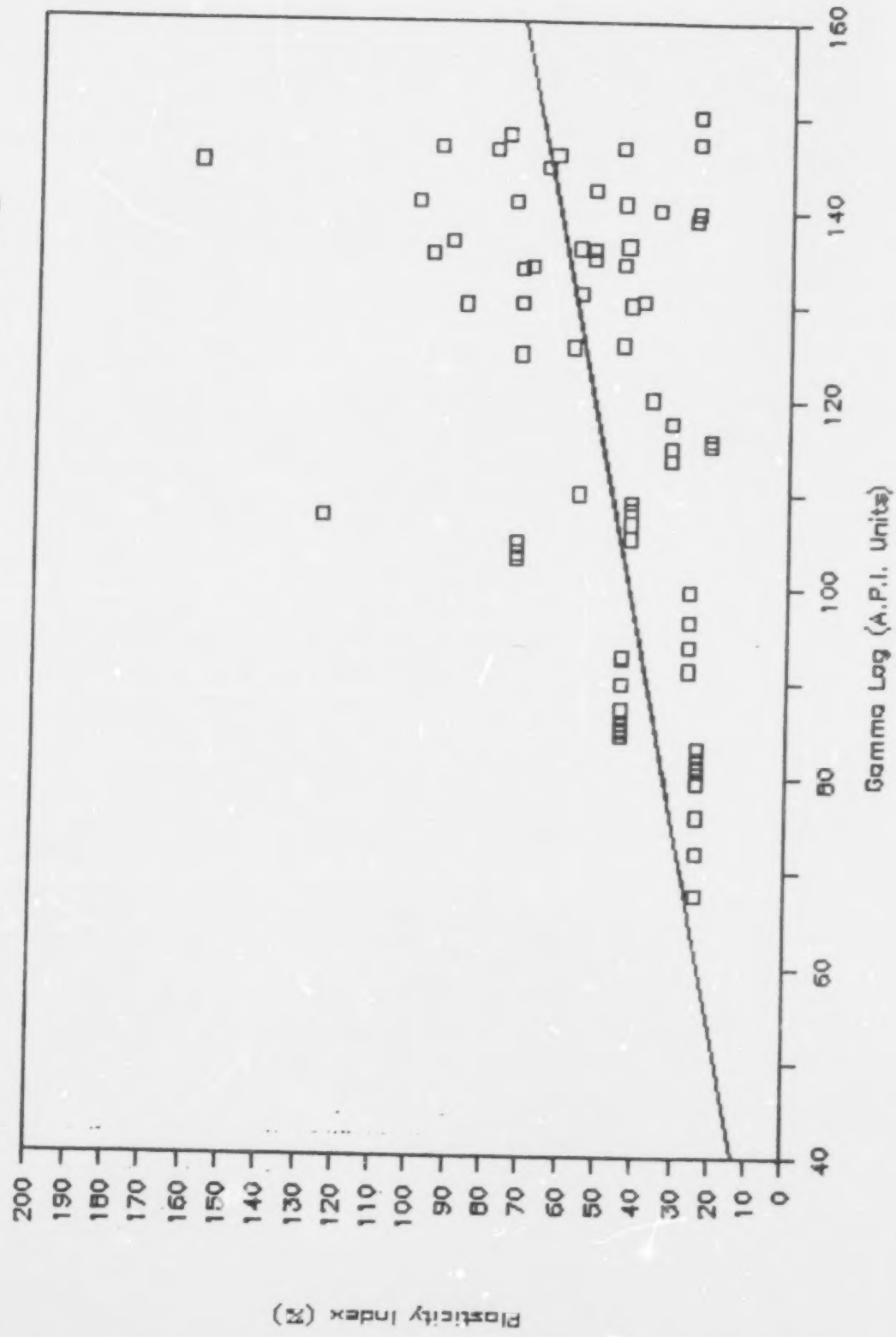
Kcb Plasticity Index vs Gamma Log



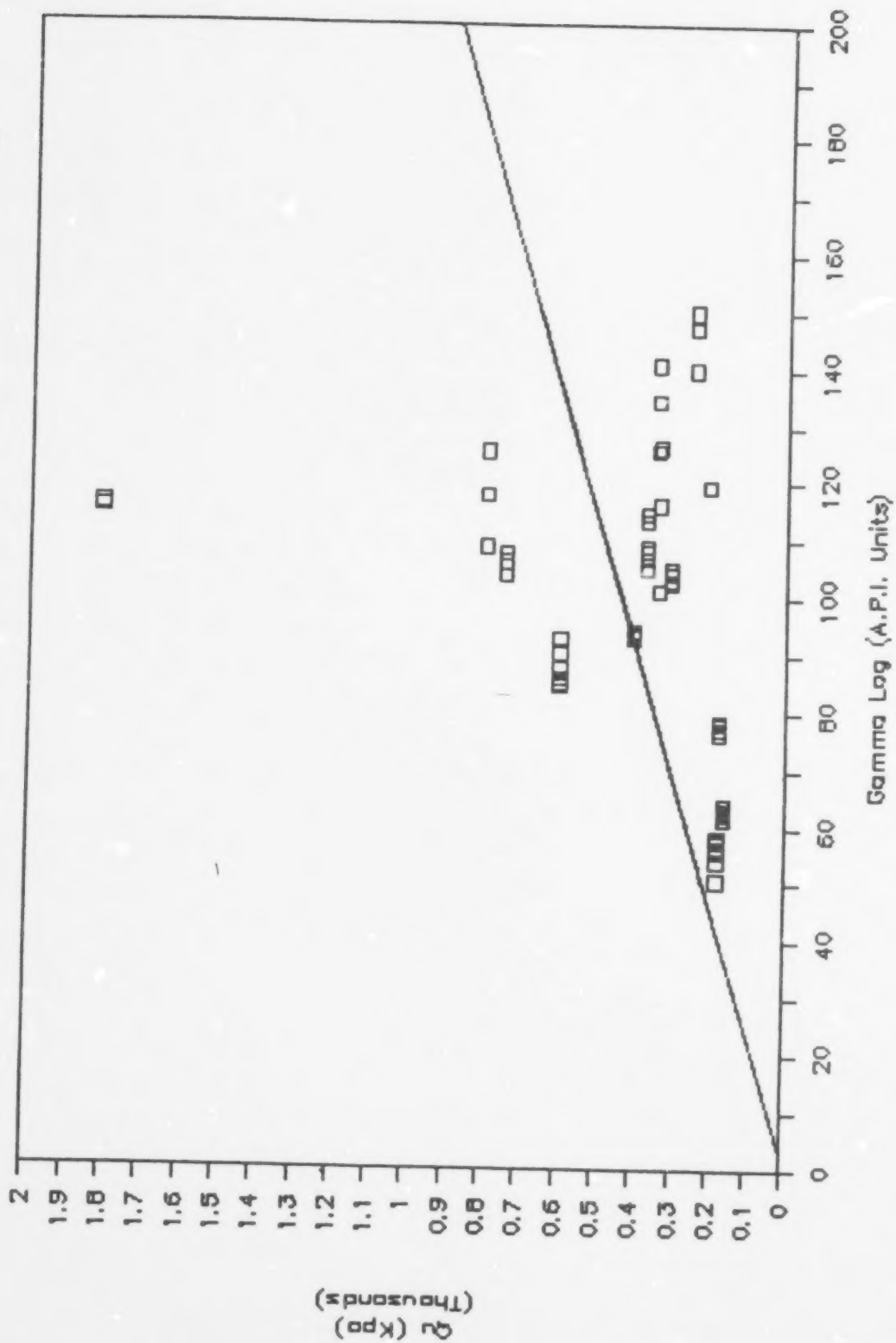
Log Kcb Plasticity Index vs Gamma Log



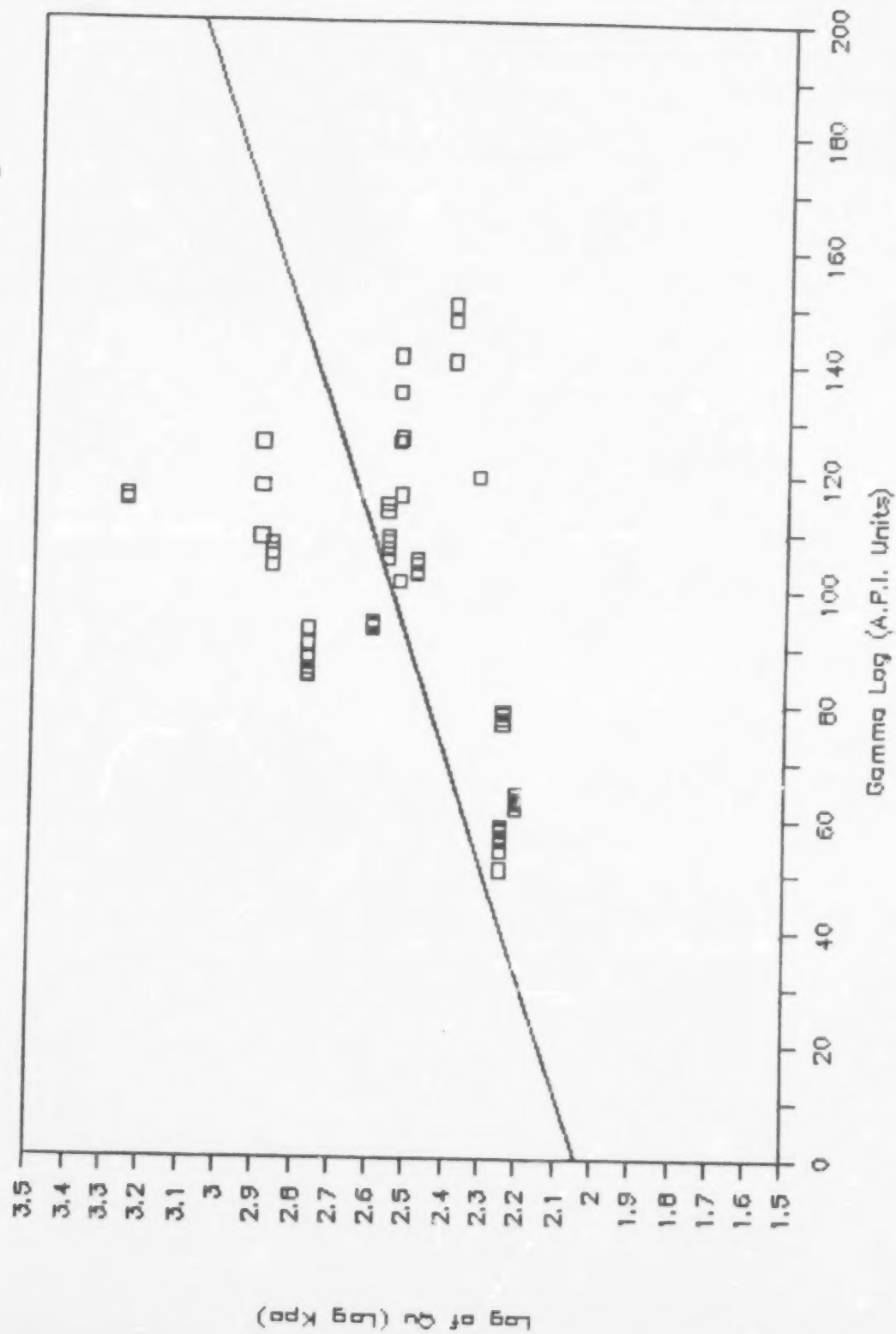
Kcc Plasticity Index vs Gamma Log



Undrained Shear Strength vs. Gamma Log



Log of Shear Strength vs Gamma Log



Regression Output for Plastic Index vs Bulk Density Log

Regression Output:

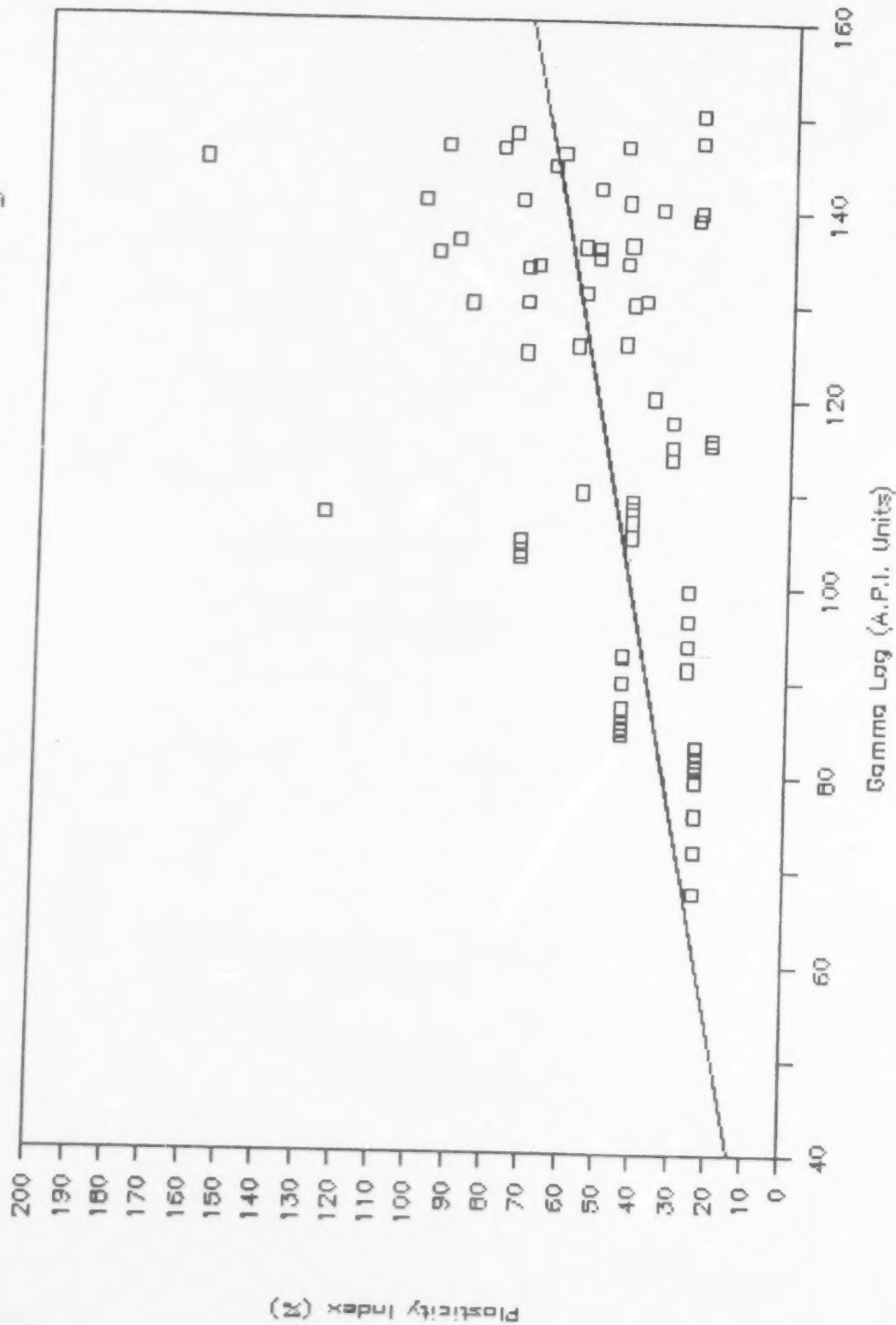
Constant	399.2752	
Std Err of Y Est	31.76982	
R Squared	0.191360	R Value 0.437447
No. of Observations	162	
Degrees of Freedom	160	
X Coefficient(s)	-157.076	
Std Err of Coef.	25.52718	Y=-157.076X+399.2752

Regression Analysis Output for
Log of Plasticity Index vs Bulk Density Log

Regression Output:

Constant	3.966550	
Std Err of Y Est	0.212613	
R Squared	0.188164	R Value 0.433778
No. of Observations	162	
Degrees of Freedom	160	
X Coefficient(s)	-1.04033	
Std Err of Coef.	0.170835	Y=-1.040X+3.967

K_{cc} Plasticity Index vs Gamma Log



Regression Analysis Output for
Undrained Shear Strength vs Gamma Log

Regression Output:

Constant	-13.7223		
Std Err of Y Est	304.7697		
R Squared	0.133160	R Value	0.365
No. of Observations	61		
Degrees of Freedom	59		

X Coefficient(s) 4.524302
Std Err of Coef. 1.502821
Y=4.524*X-13.722

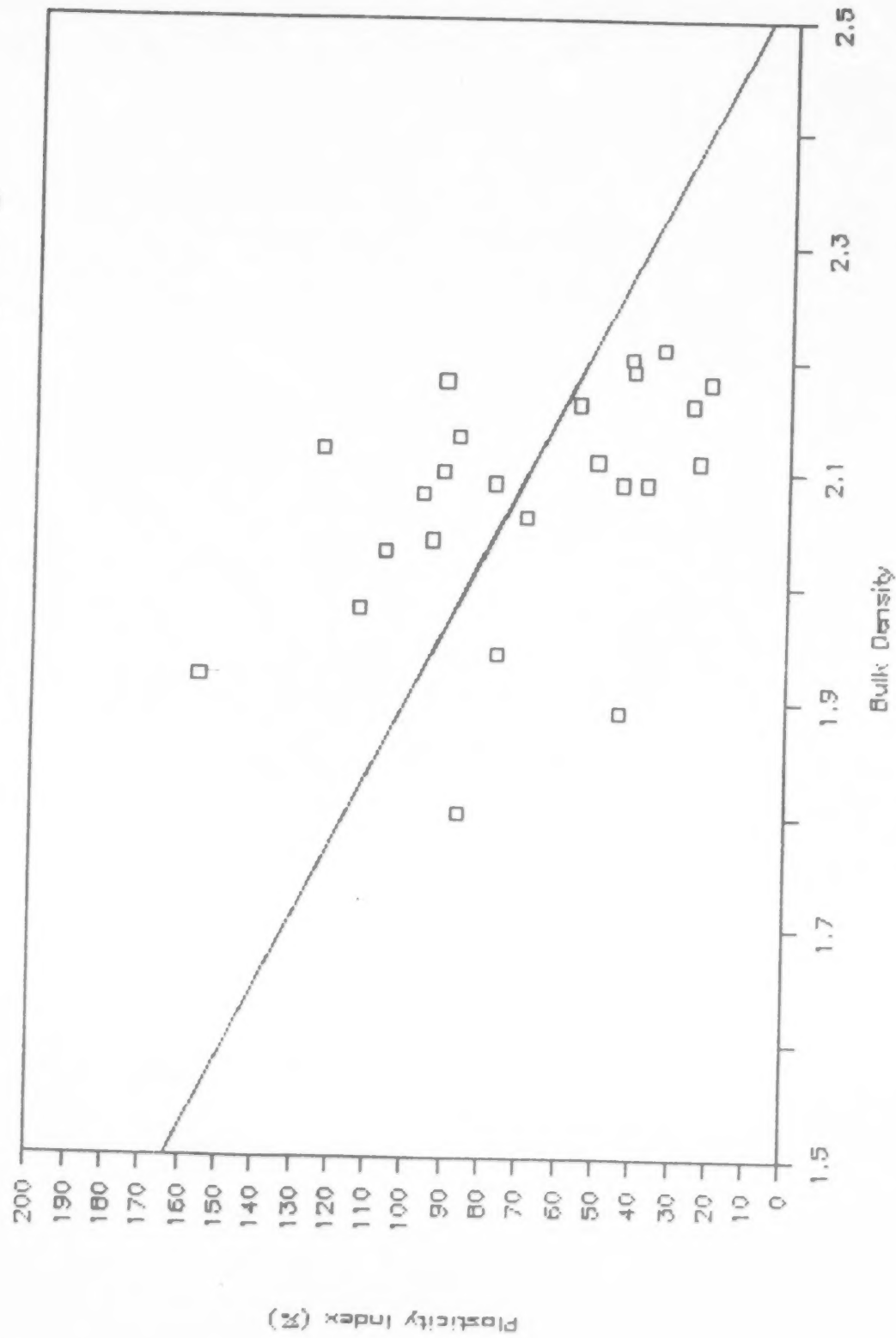
Regression Output for
Log of Undrained Shear Strength vs Gamma Log

Regression Output:

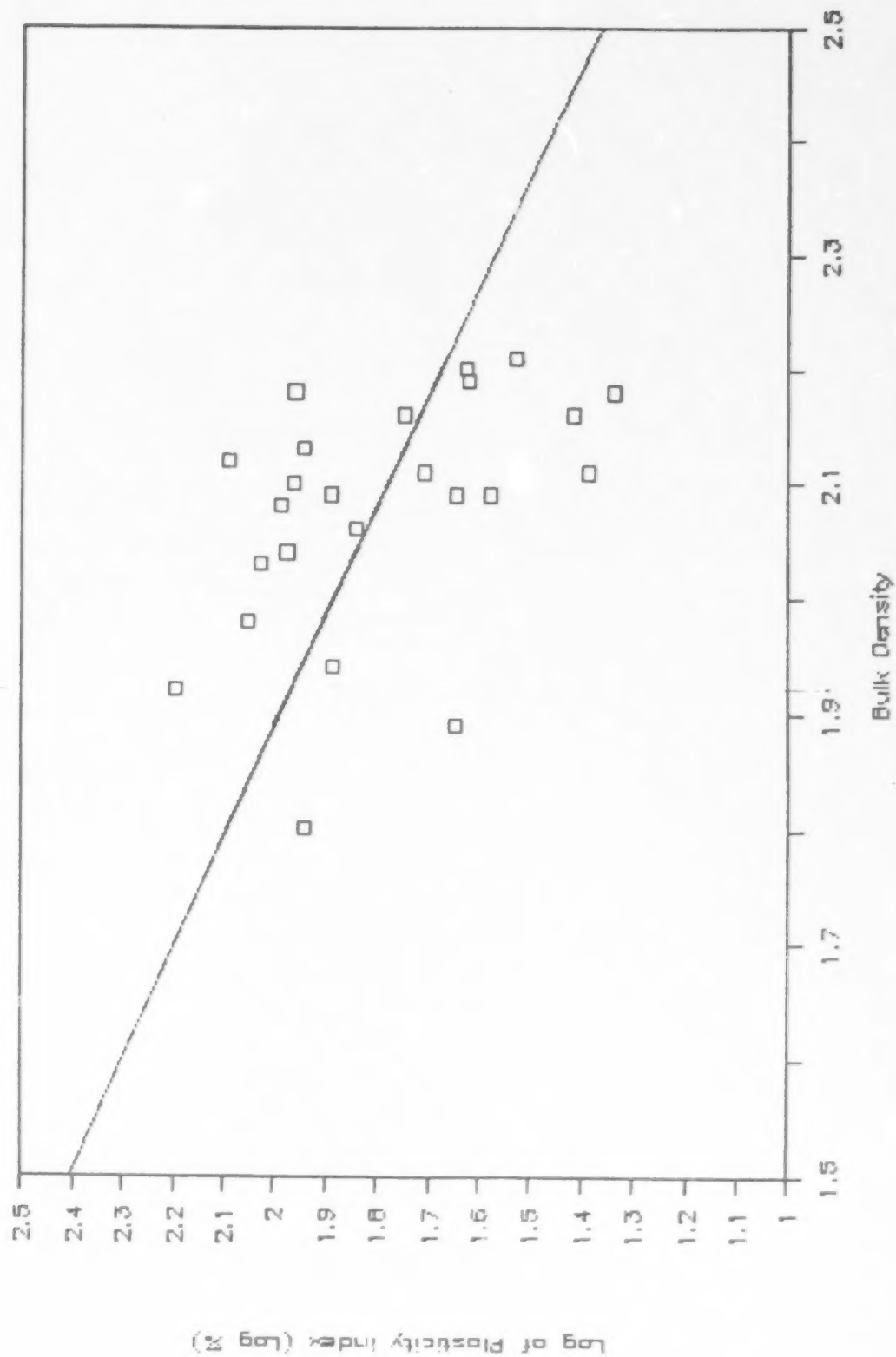
Constant	2.038909		
Std Err of Y Est	0.227086		
R Squared	0.266240	R Value	0.515984
No. of Observations	61		
Degrees of Freedom	59		

X Coefficient(s) 0.005180
Std Err of Coef. 0.001119
Y=0.005*X+2.039

Plasticity Index vs Bulk Density Log



Log Plastic Index vs Bulk Density Log



Regression Analysis Output for
Moisture Content (%) vs Resistivity Log

Regression Output:

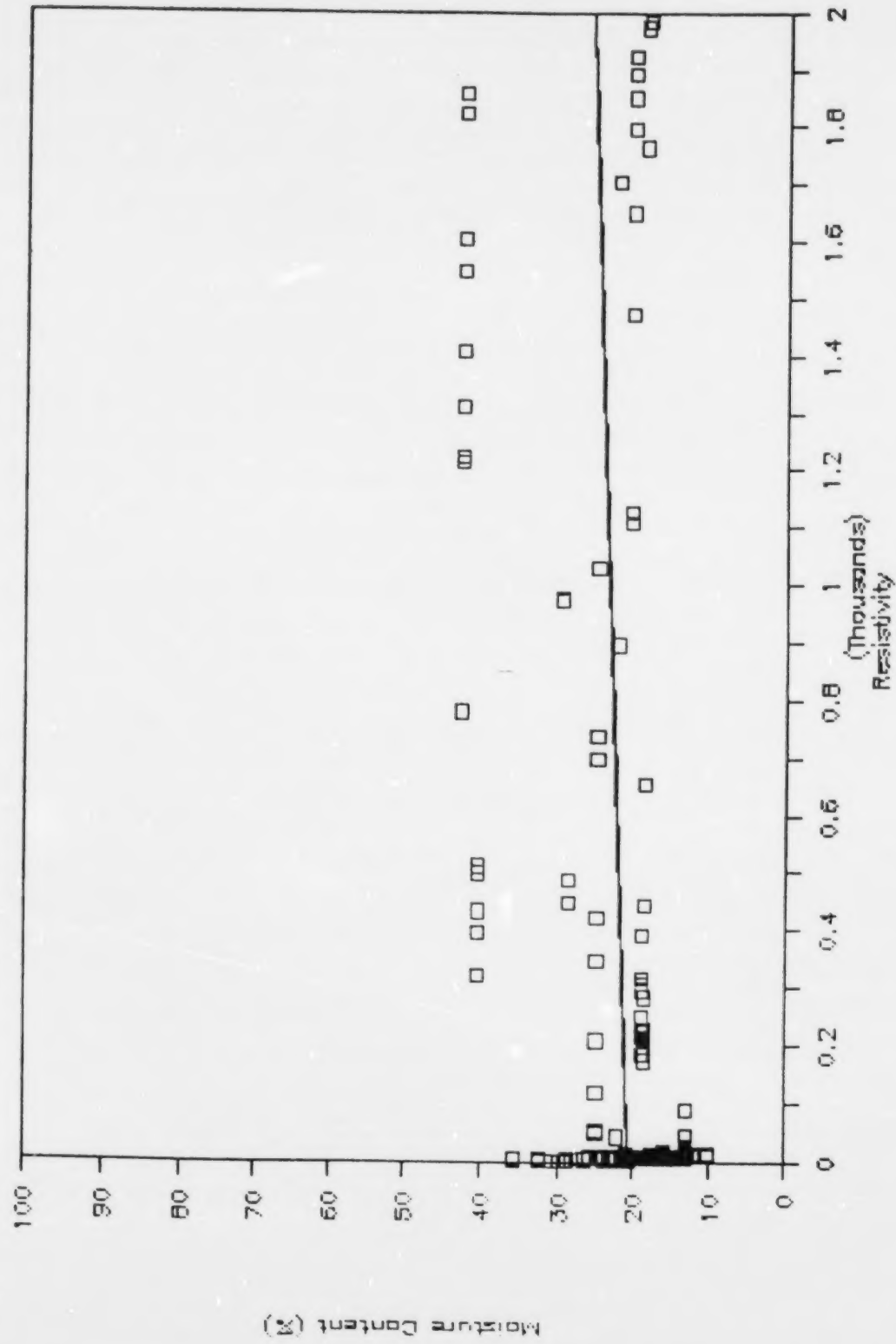
Constant	20.616		
Std Err of Y Est	7.191		
R Squared	0.065	R Value	0.254
No. of Observations	238.000		
Degrees of Freedom	236.000		
X Coefficient(s)	0.003		
Std Err of Coef.	0.001		$Y=0.003 \times X + 20.616$

Regression Analysis Output for
Log of Moisture Content (Log%) vs Resistivity Log

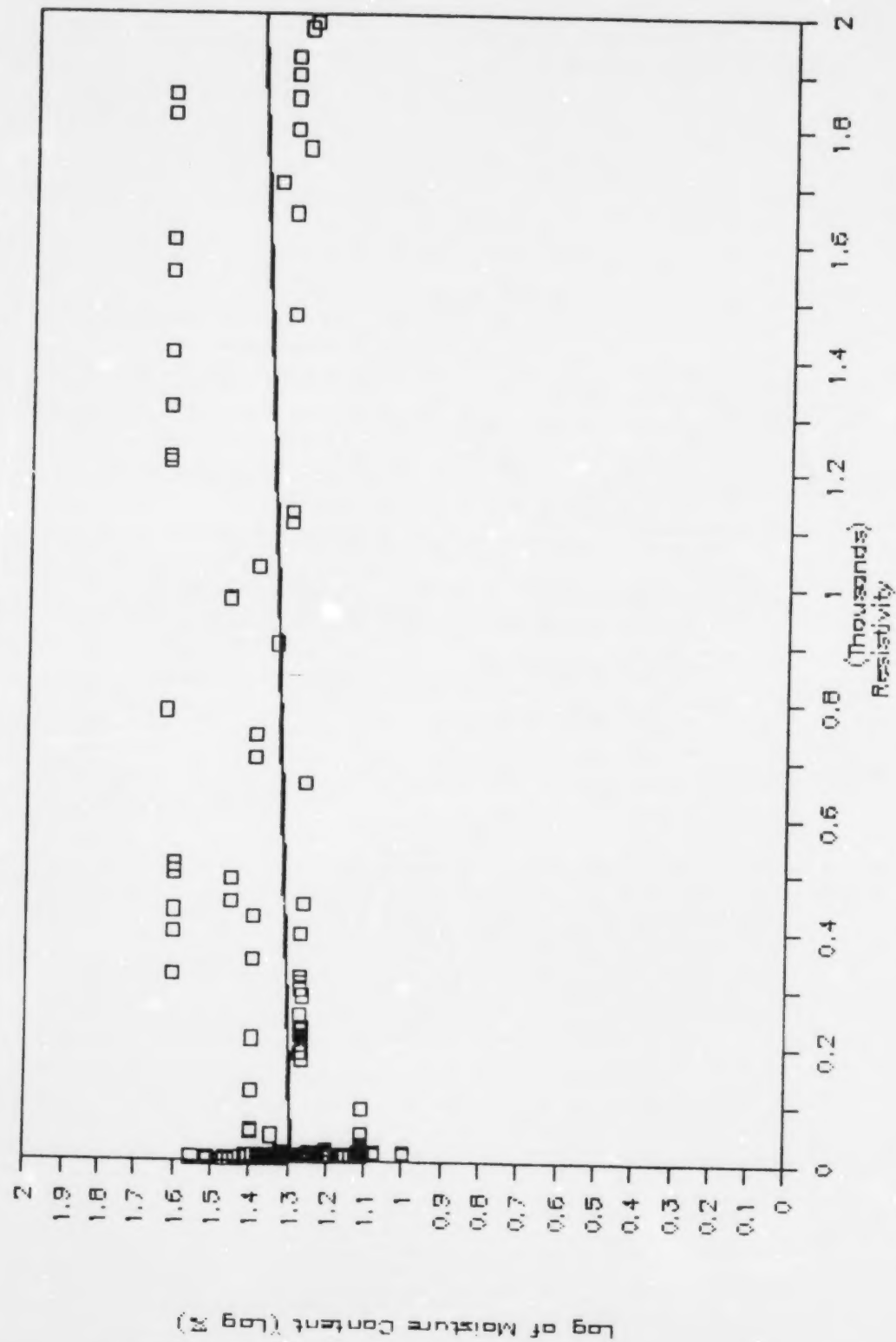
Regression Output:

Constant	1.293		
Std Err of Y Est	0.134		
R Squared	0.067	R Value	0.259
No. of Observations	238.000		
Degrees of Freedom	236.000		
X Coefficient(s)	5.50E-05		
Std Err of Coef.	1.33E-05		$Y=5.50E-05 \times X + 1.293$

Moisture Content (%) vs Resistivity Log



Moisture Content vs Resistivity Log



Regression Analysis Output for
Fines Content (%) vs Resistivity Log

Regression Output:

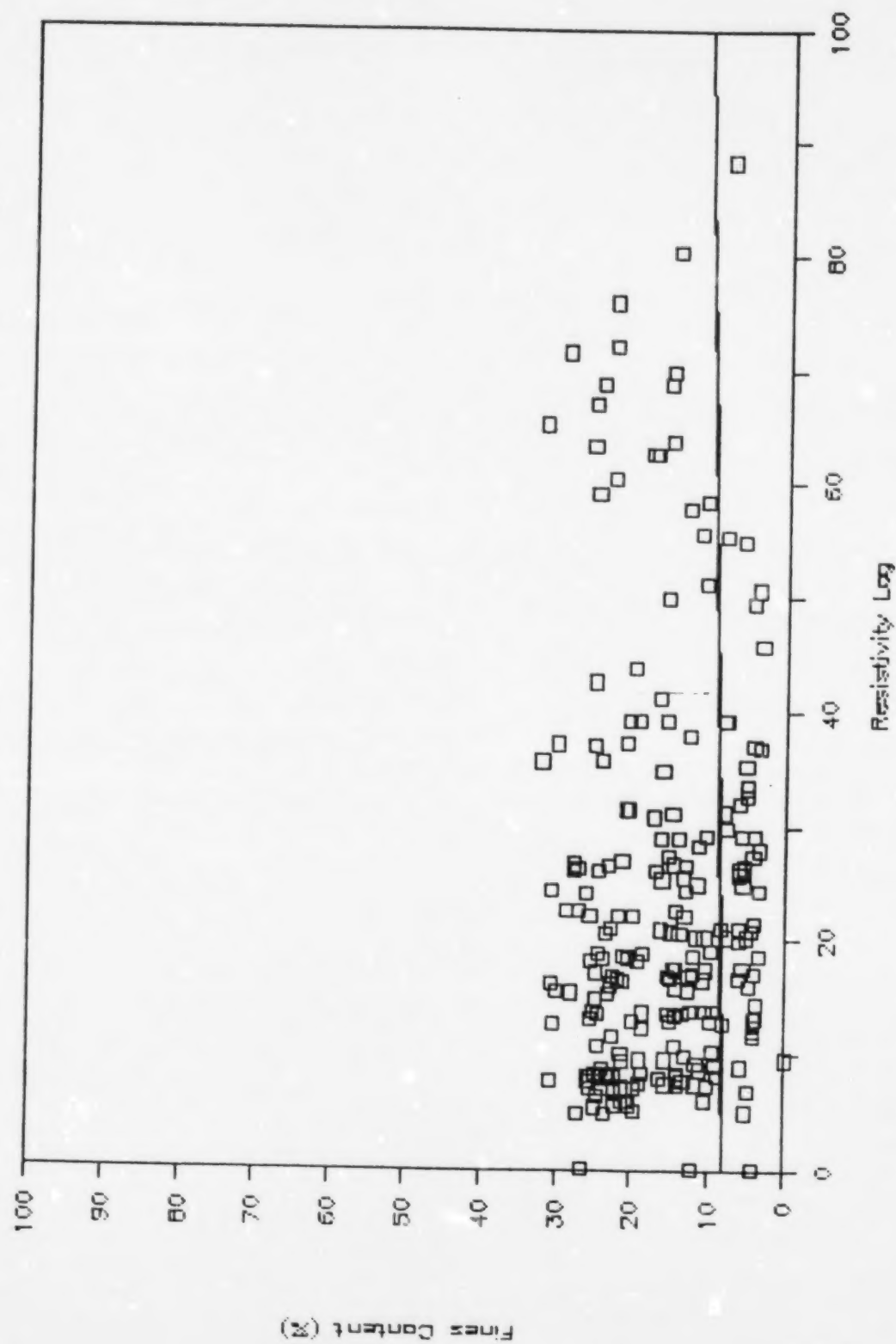
Constant	16.330		
Std Err of Y Est	7.879		
R Squared	0.001	R Value	0.024
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	-0.011		
Std Err of Coef.	0.031		$Y = -0.011 \times X + 16.330$

Regression Analysis Output for
Log of Fines Content (Log %) vs Resistivity Log

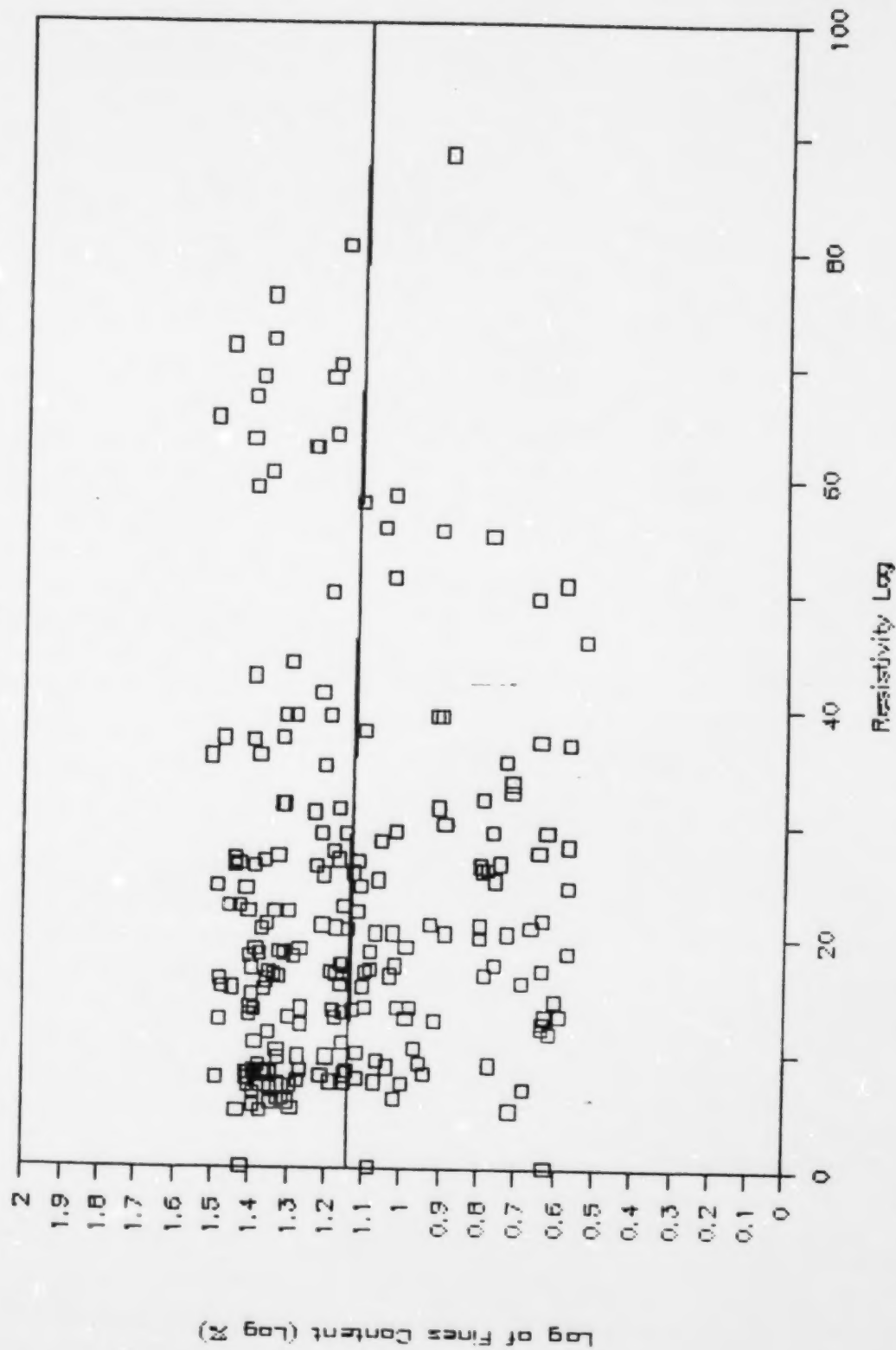
Regression Output:

Constant	1.143		
Std Err of Y Est	0.275		
R Squared	0.00039	R Value	0.020
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	-0.00031		
Std Err of Coef.	0.001		$Y = -0.0003 \times X + 1.143$

Fines Content (%) vs Resistivity Log



Fine Content (Log%) vs Resistivity Log



Regression Analysis Output for
Fines Content (%) vs Neutron Porosity Log

Regression Output:

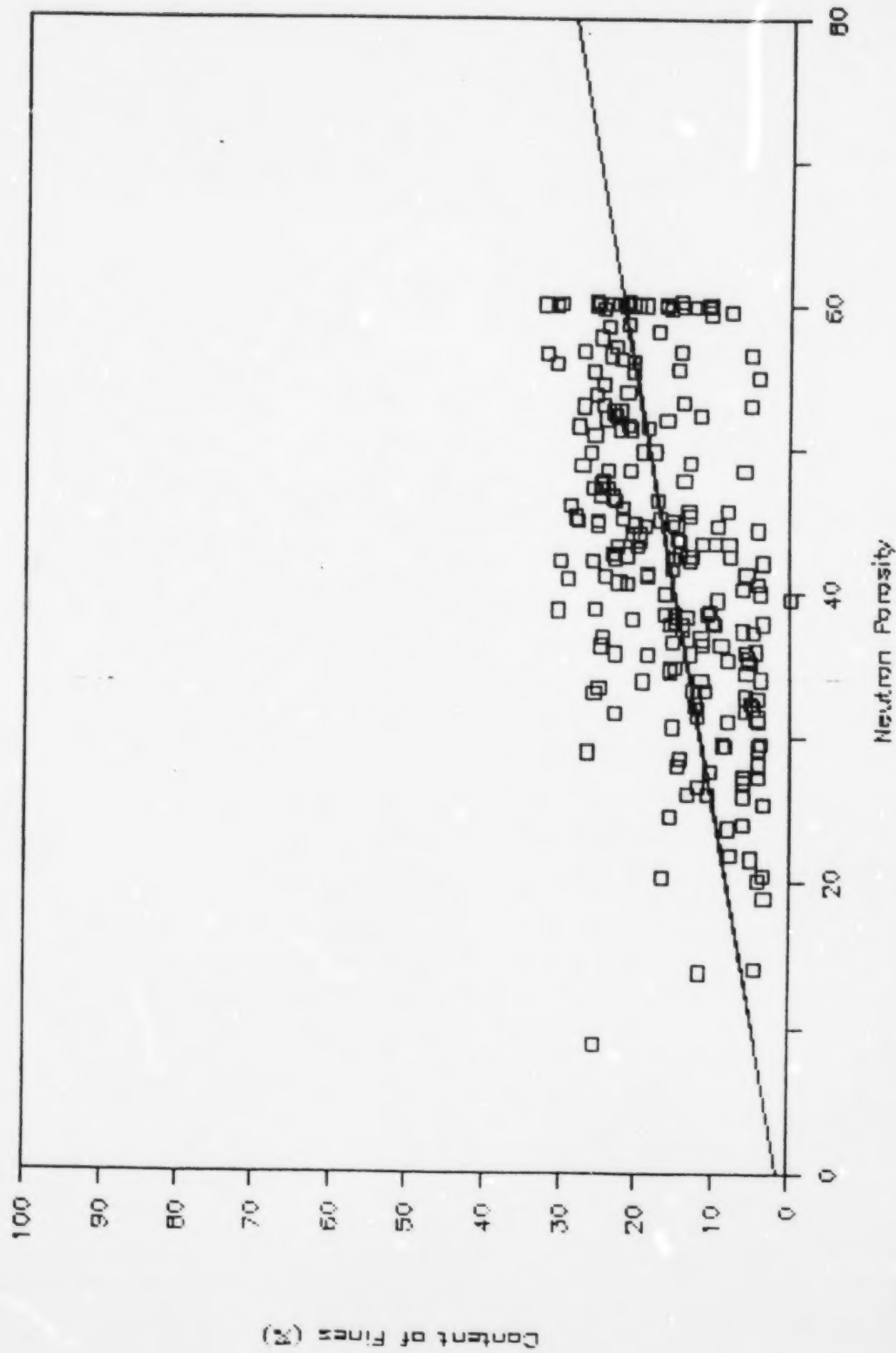
Constant	1.481	
Std Err of Y Est	6.878	
R Squared	0.238	R Value 0.48832
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	0.340	
Std Err of Coef.	0.041	Y=0.340X+1.418

Regression Analysis Output for
Log of Fines Content (Log %) vs Neutron Porosity Log

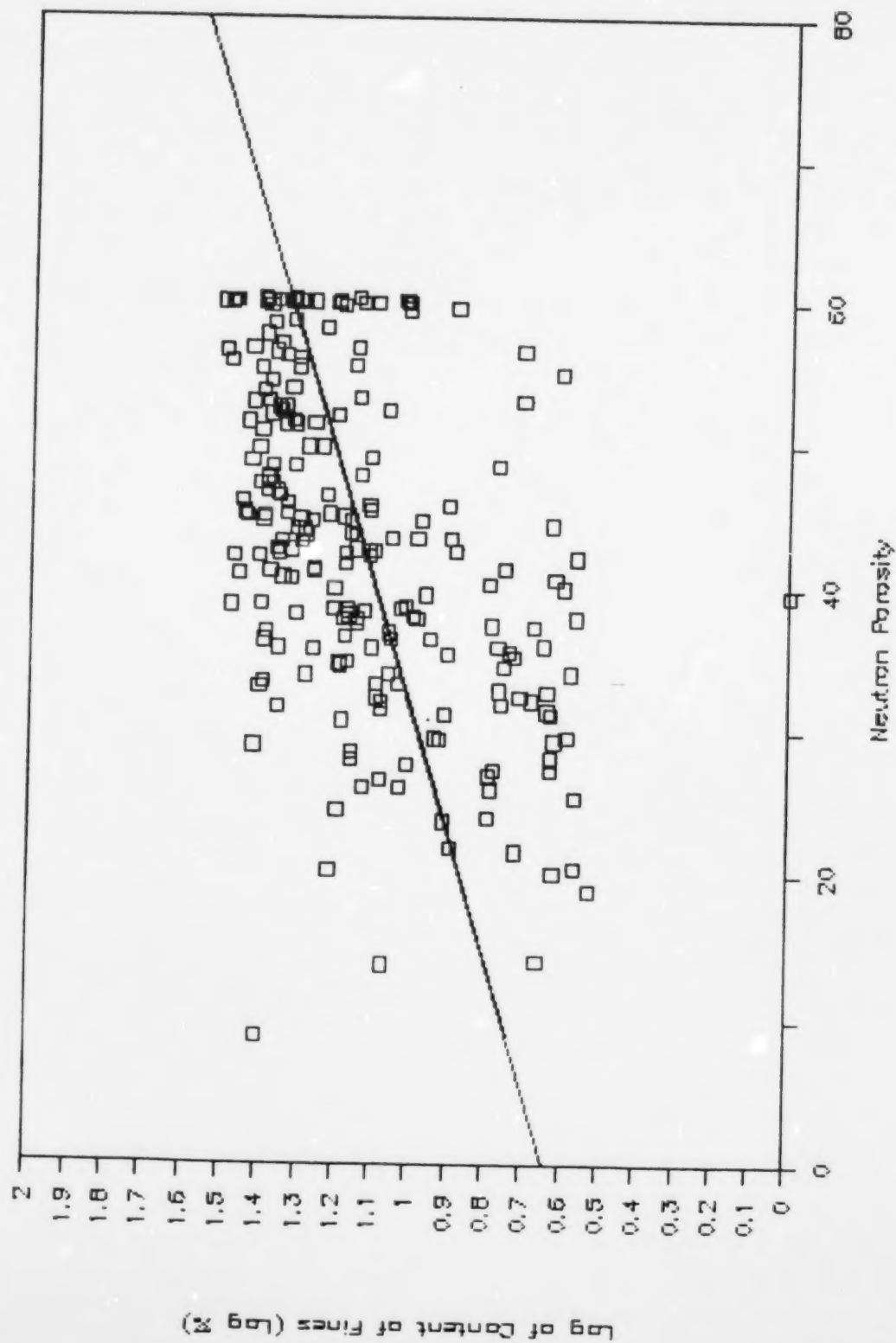
Regression Output:

Constant	0.634	
Std Err of Y Est	0.241	
R Squared	0.232	R Value 0.49068
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	0.012	
Std Err of Coef.	0.001	Y=0.012X+0.634

Fine Content(%) vs Neutron Porosity Log



Log Fine Content vs Neutron Porosity



Regression Analysis Output for
Fines Content (%) vs Density Porosity

Regression Output:

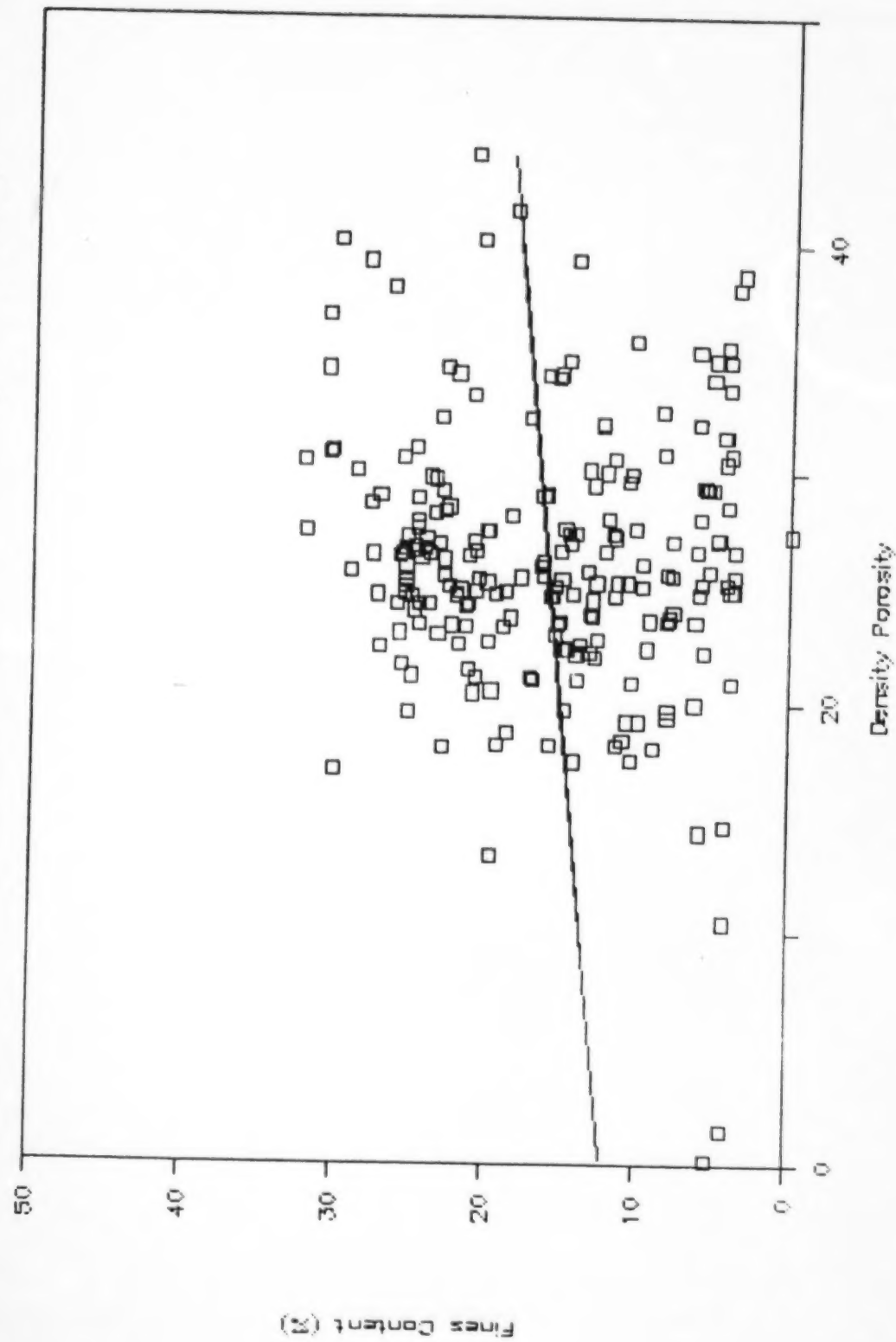
Constant	12.159		
Std Err of Y Est	7.834		
R Squared	0.012	R Value	0.110
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.149		
Std Err of Coef.	0.092		Y=0.149*X+12.159

Regression Analysis Output for
Log of Fines Content (Log %) vs Density Porosity

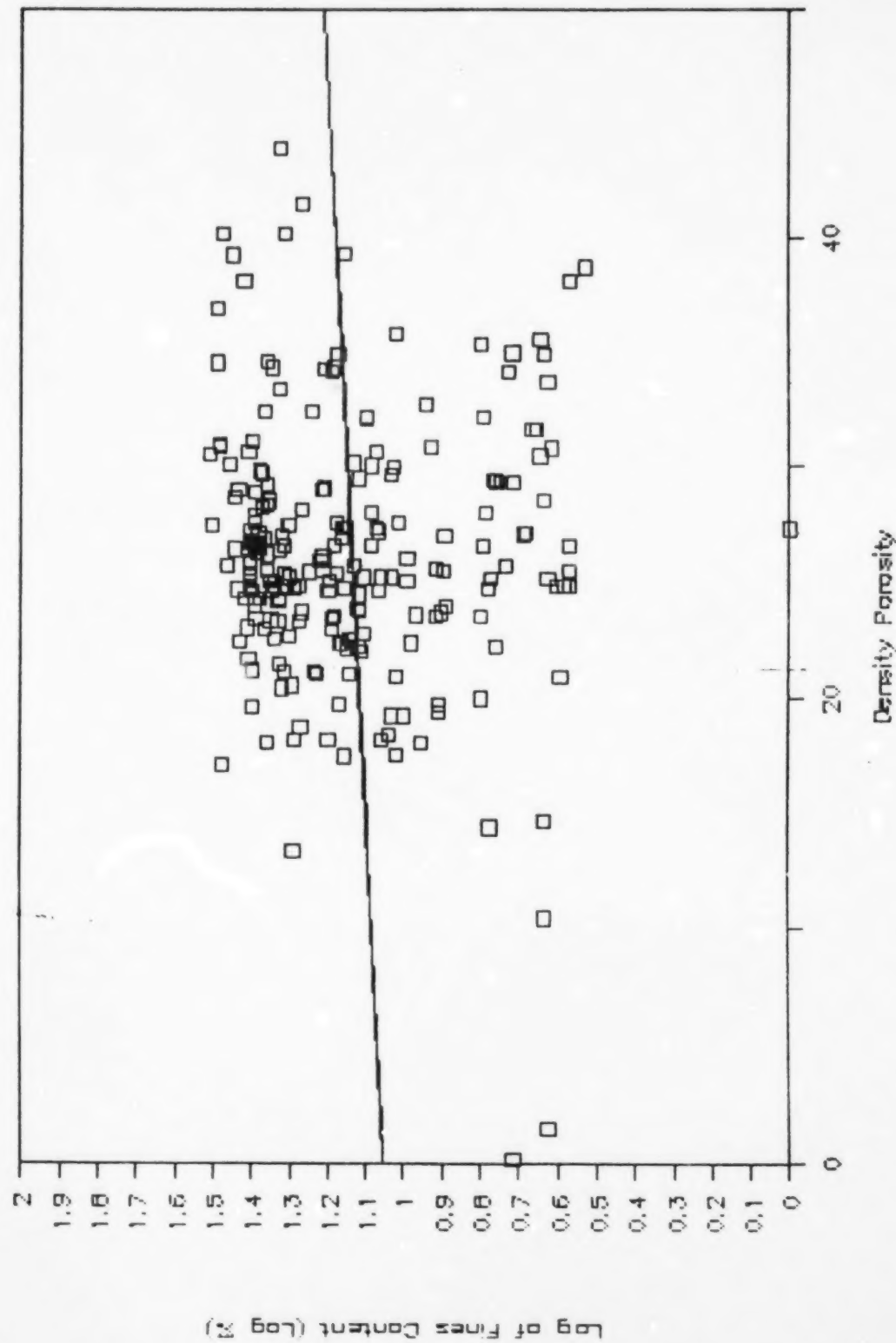
Regression Output:

Constant	1.053		
Std Err of Y Est	0.274		
R Squared	0.004	R Value	0.067
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.003		
Std Err of Coef.	0.003		Y=0.003*X+1.053

Fines Content (%) vs Density Porosity



Log Fines Content vs Density Porosity



Regression Analysis Output for
Fines Content (%) vs Gamma Log

Regression Output:

Constant	-9.296		
Std Err of Y Est	6.946		
R Squared	0.223	R Value	0.472
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.276		
Std Err of Coef.	0.035		

$Y = 0.276X - 9.296$

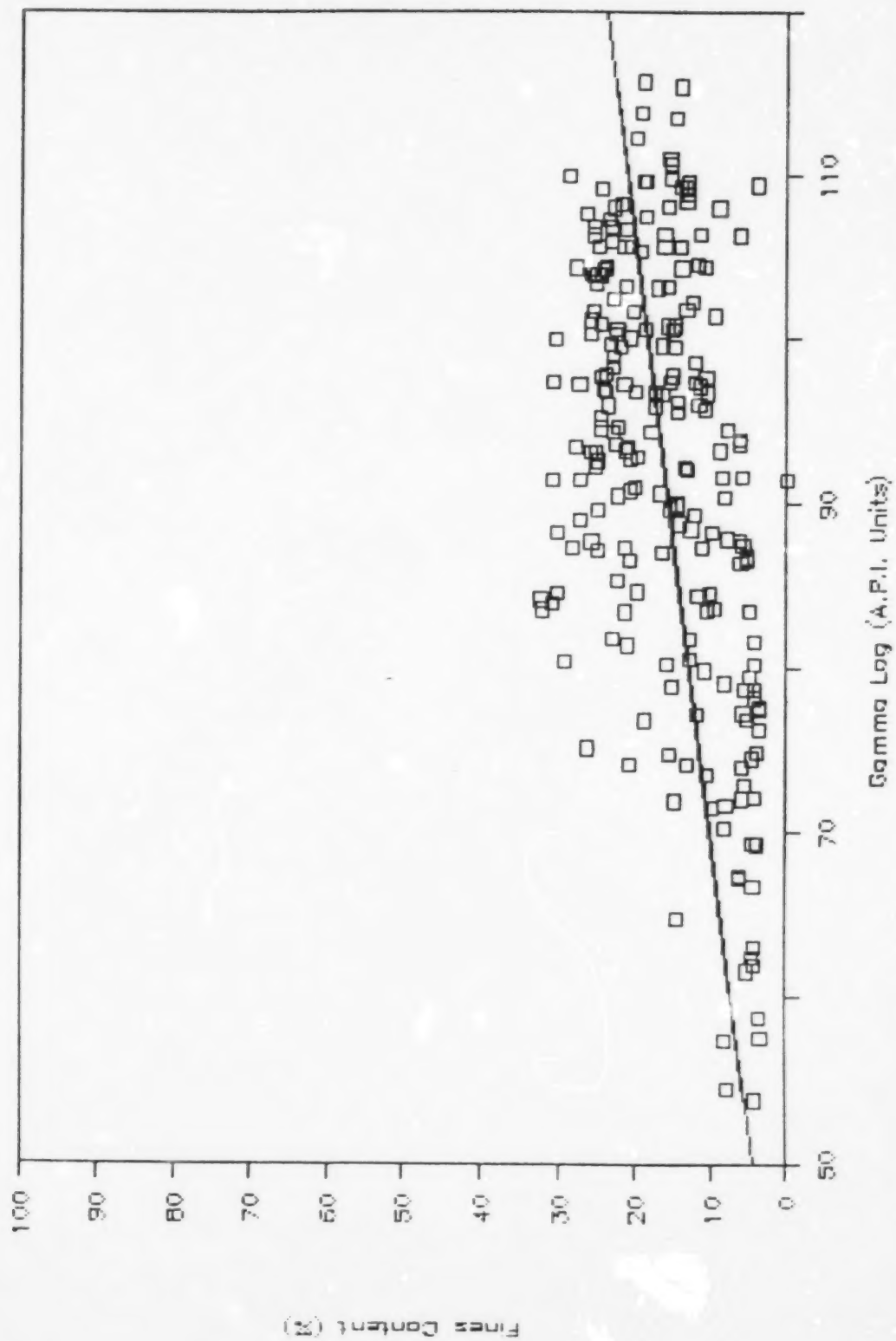
Regression Analysis Output for
Log of Fines Content (Log %) vs Gamma Log

Regression Output:

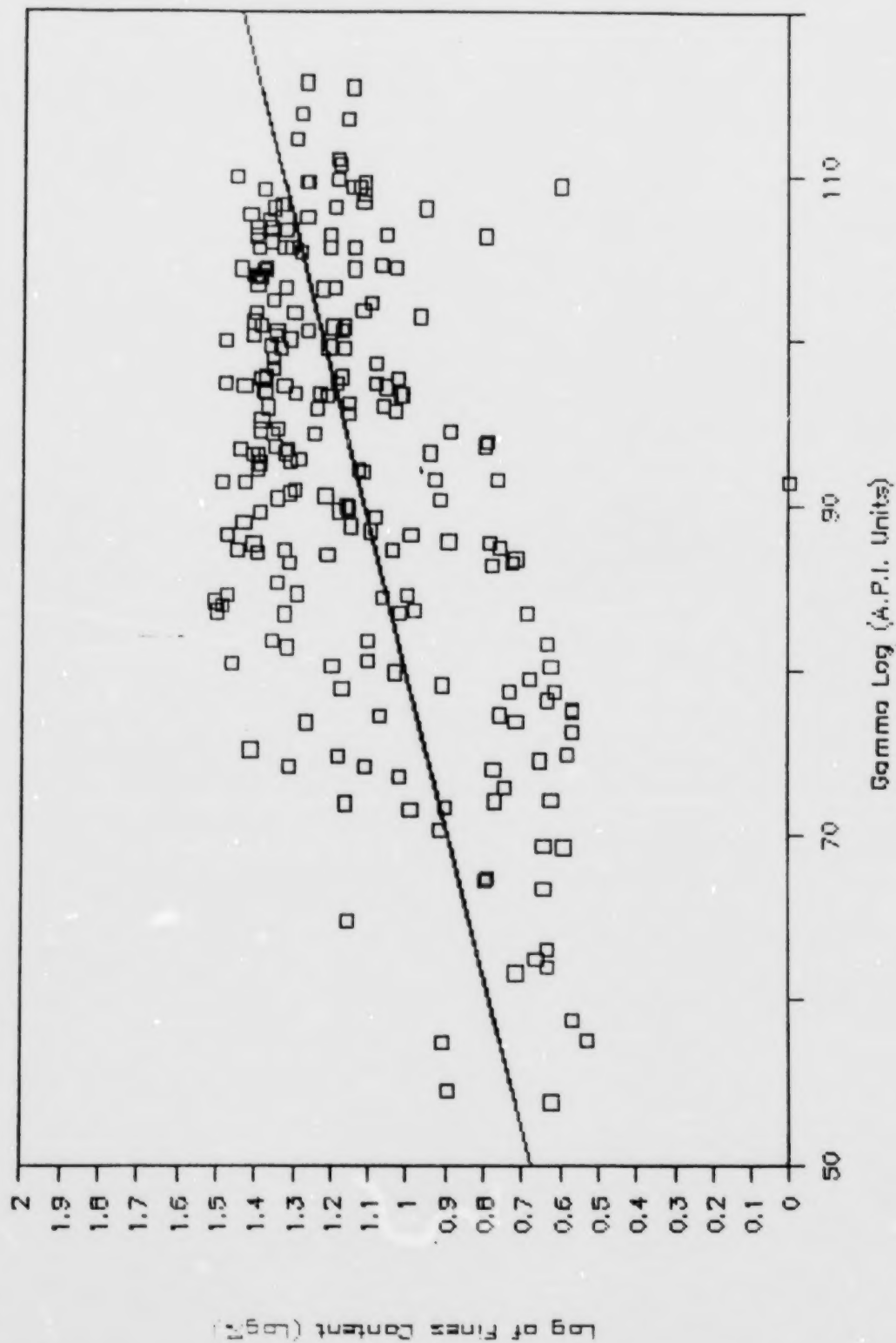
Constant	0.125		
Std Err of Y Est	0.231		
R Squared	0.292	R Value	0.540
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.011		
Std Err of Coef.	0.001		

$Y = 0.011X + 0.125$

Fines Content (%) vs Gamma Log



Log of Fines Content(Log%) vs Gamma Log



Regression Analysis Output for
Silt Content (%) vs Resistivity Log

Regression Output:

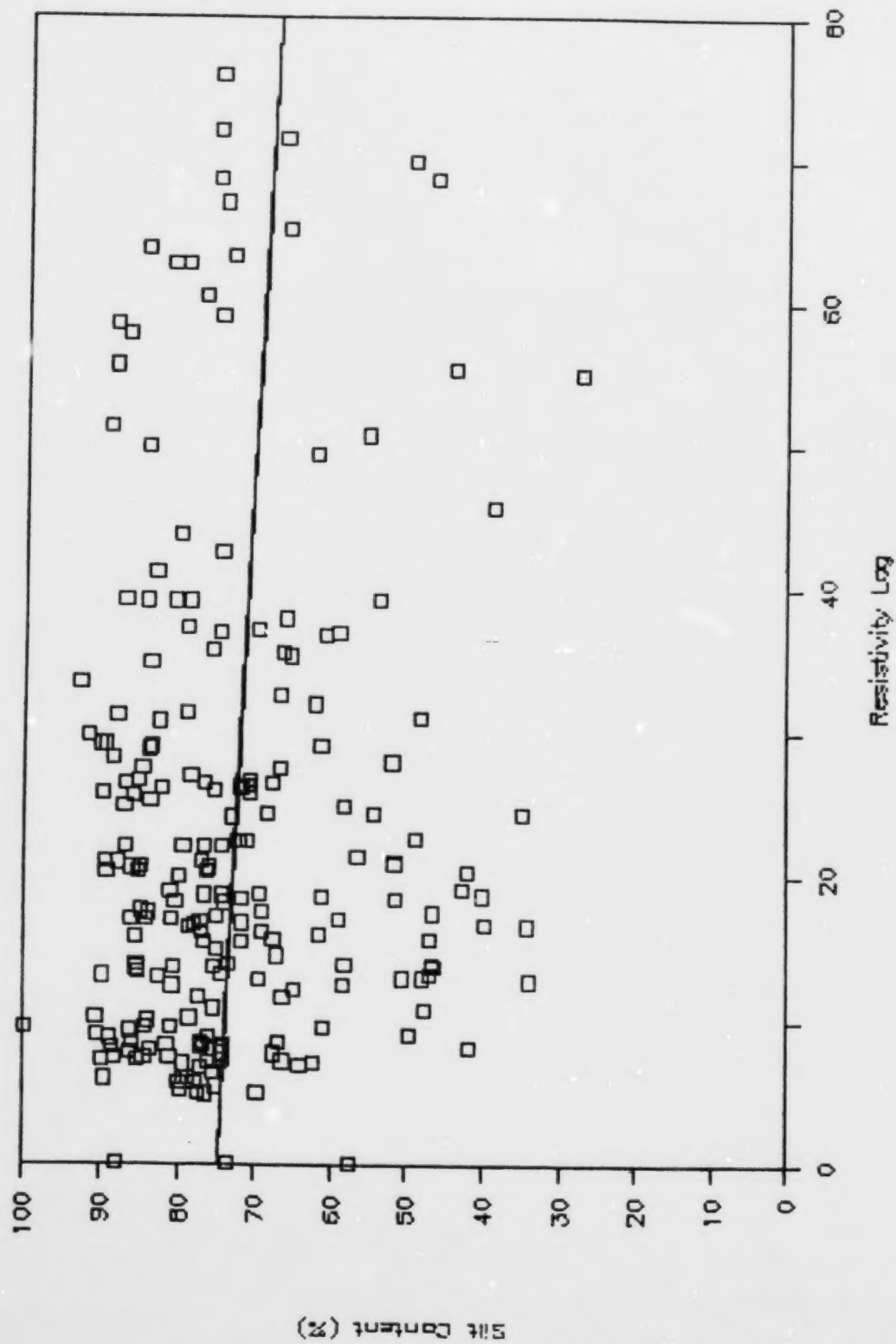
Constant	74.774	
Std Err of Y Est	13.967	
R Squared	0.012	R Value 0.109073
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.087	
Std Err of Coef.	0.054	Y=-0.087*X+74.744

Regression Analysis Output for
Log of Fines Content (Log %) vs Resistivity Log

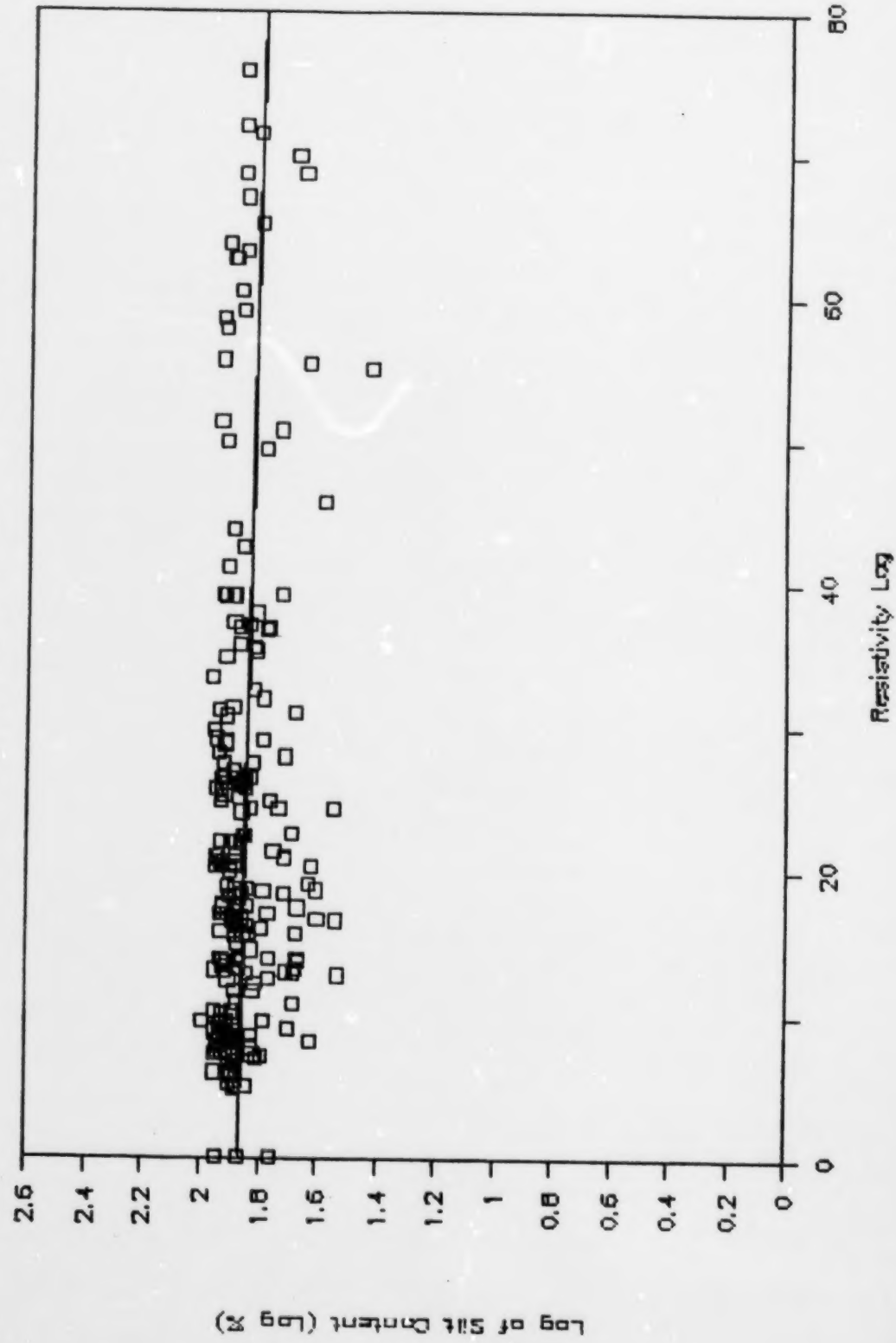
Regression Output:

Constant	1.867	
Std Err of Y Est	0.097	
R Squared	0.013	R Value 0.114
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.001	
Std Err of Coef.	0.000	Y=-0.001*X+1.867

Silt Content (%) vs Resistivity Log



Log Silt Content (%) vs Resistivity Log



Regression Analysis Output for
Silt Content (%) vs Neutron Porosity Log

Regression Output:

Constant	67.688		
Std Err of Y Est	13.988		
R Squared	0.009	R Value	0.094
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.117		
Std Err of Coef.	0.084		

$Y = 0.117 * X + 67.688$

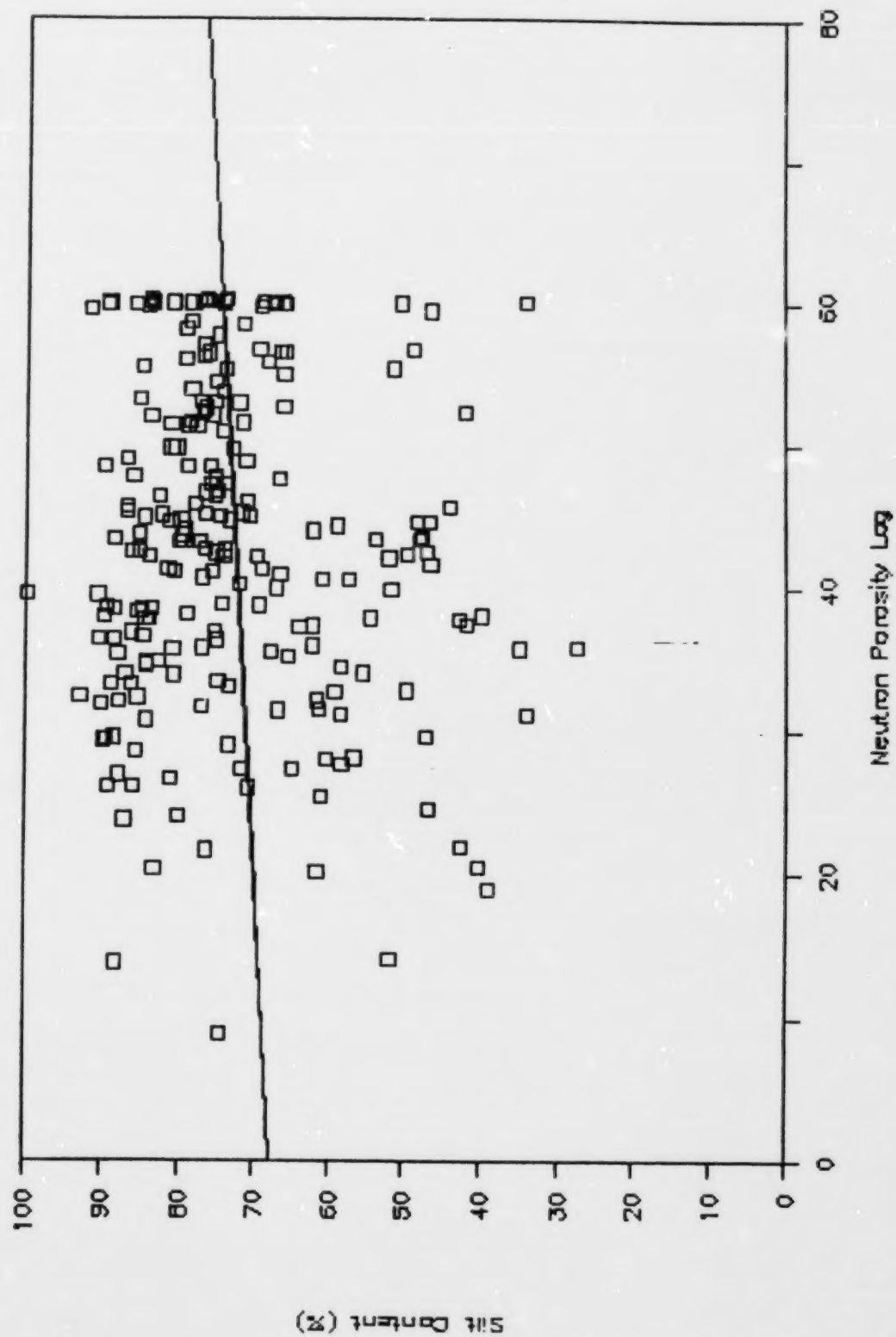
Regression Analysis Output for
Log of Silt Content (Log %) vs Neutron Porosity Log

Regression Output:

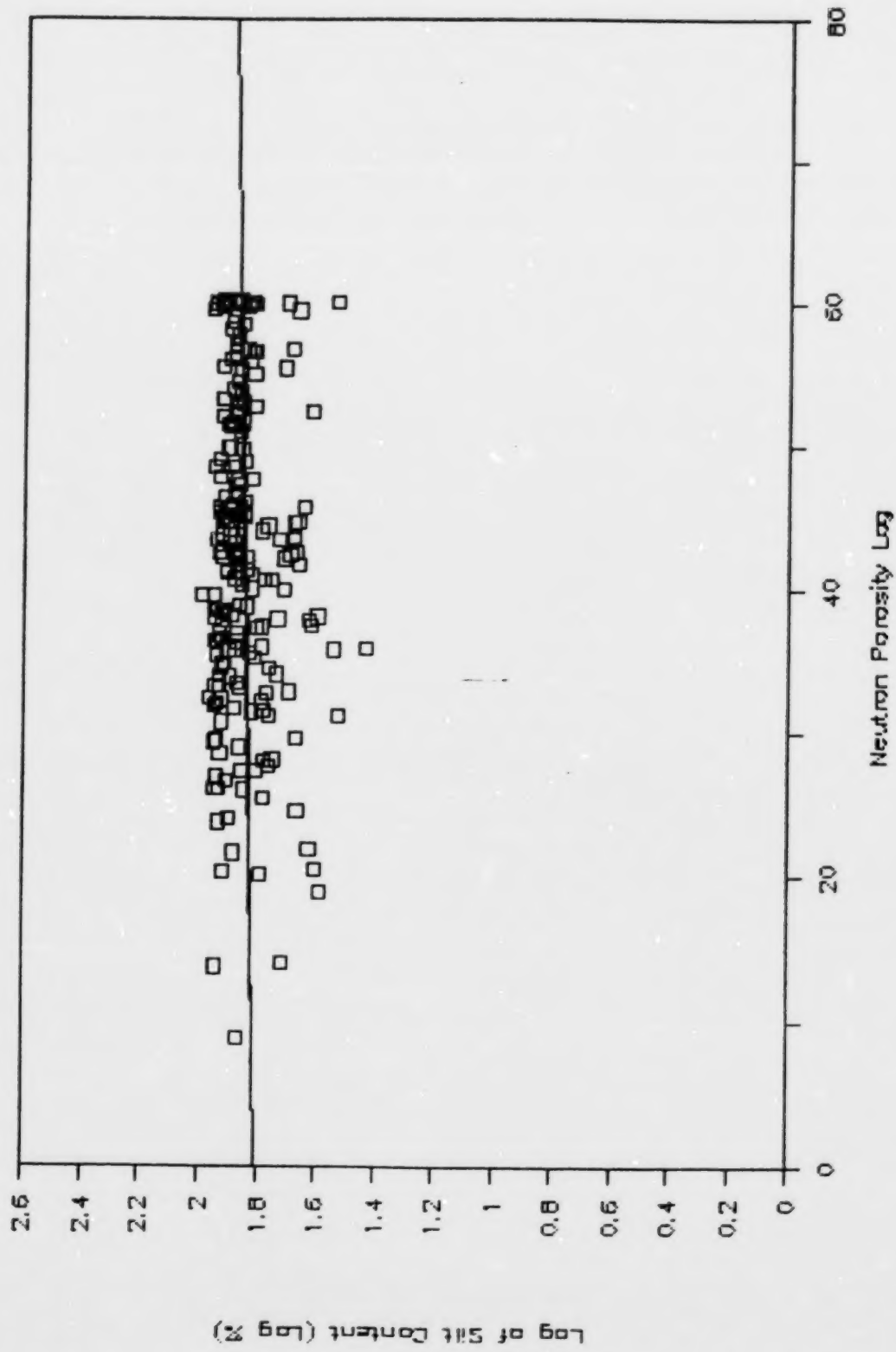
Constant	1.808		
Std Err of Y Est	0.097		
R Squared	0.014	R Value	0.117
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.001		
Std Err of Coef.	0.001		

$Y = 0.001 * X + 1.808$

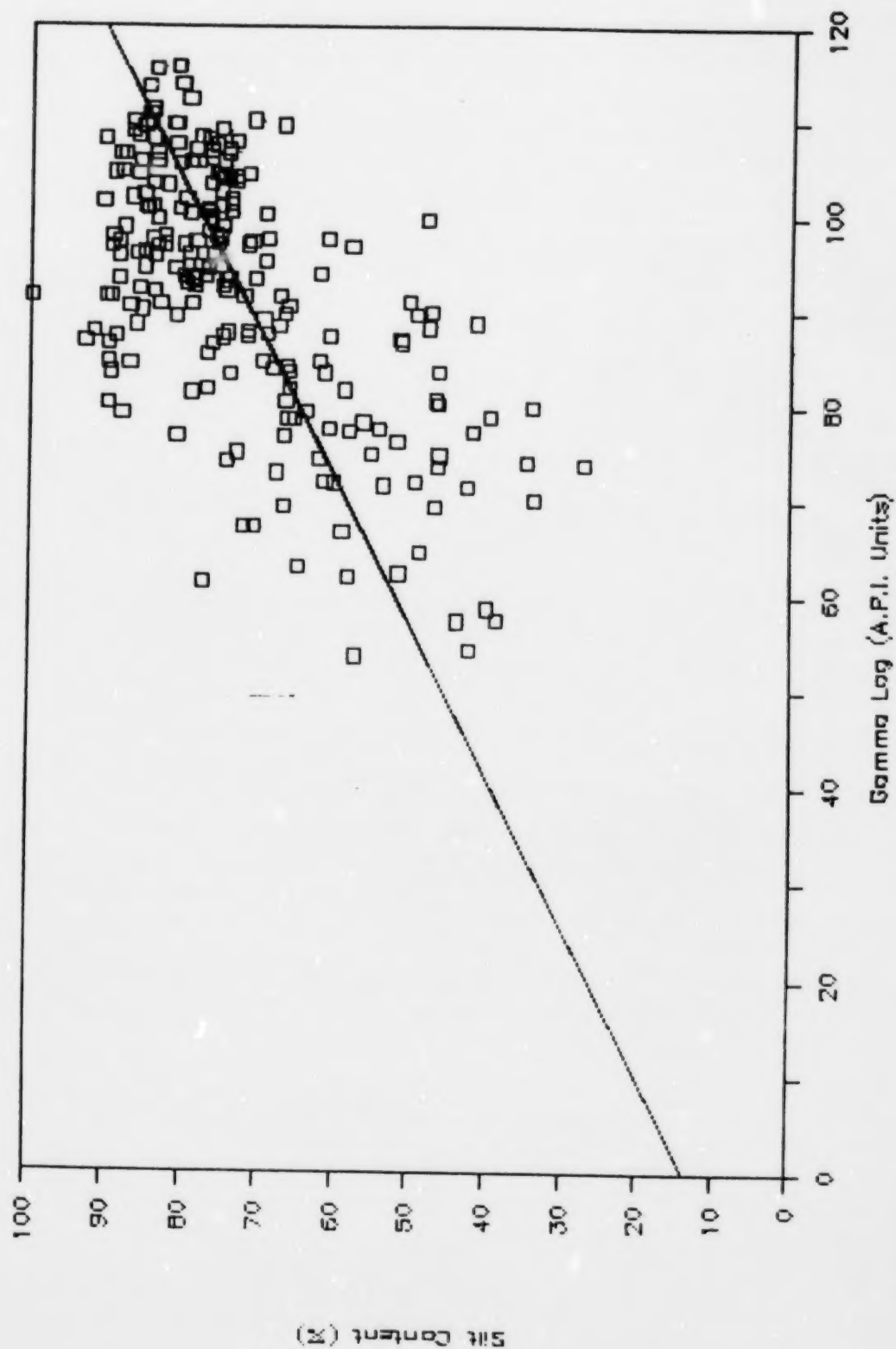
Silt Content (%) vs Neutron Porosity



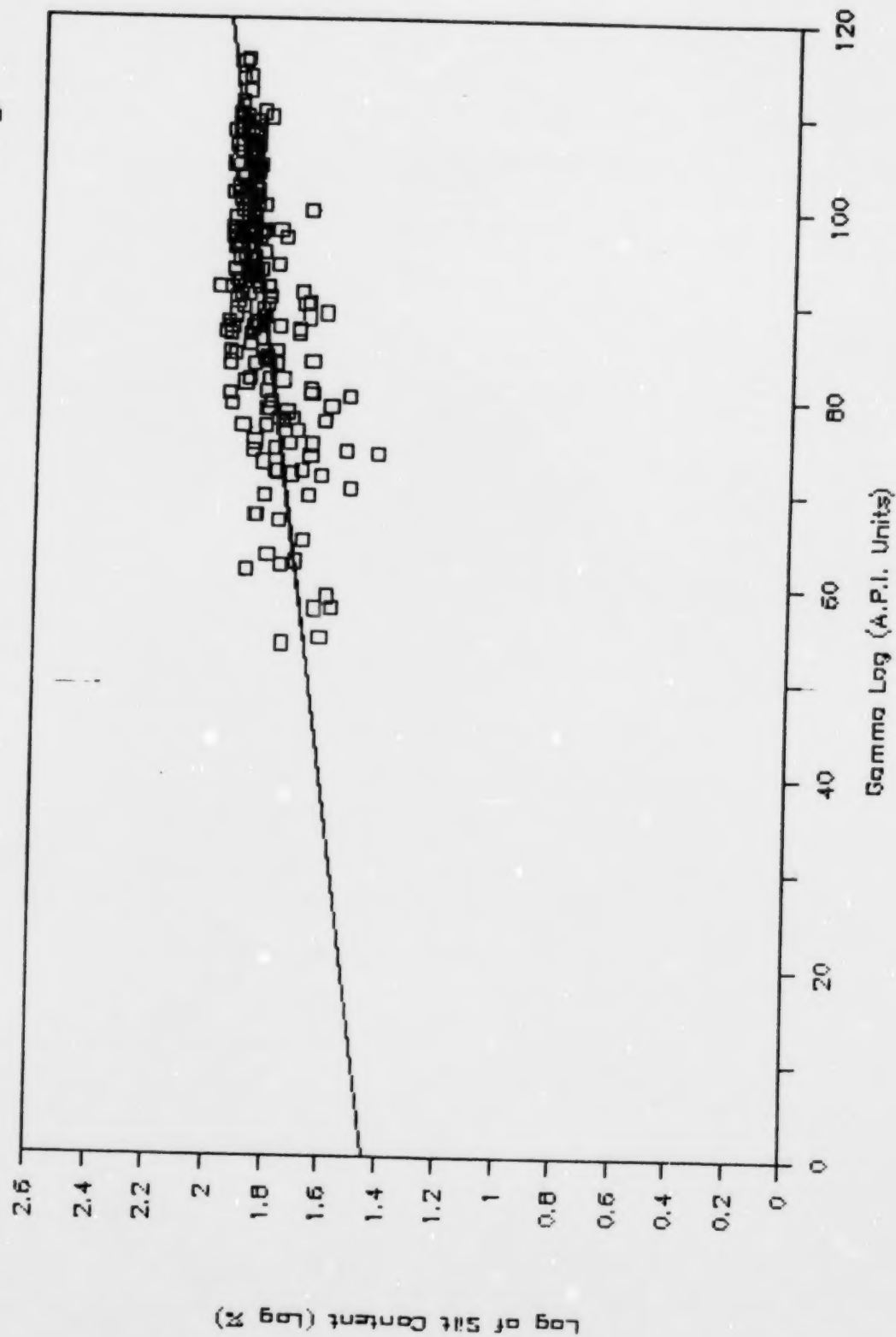
Log of Silt Content vs Neutron Porosity



Silt Content (%) vs Gamma Log



Log of Silt Content(Log %) vs Gamma Log



Regression Analysis Output for
Silt Content (%) vs Density Porosity

Regression Output:

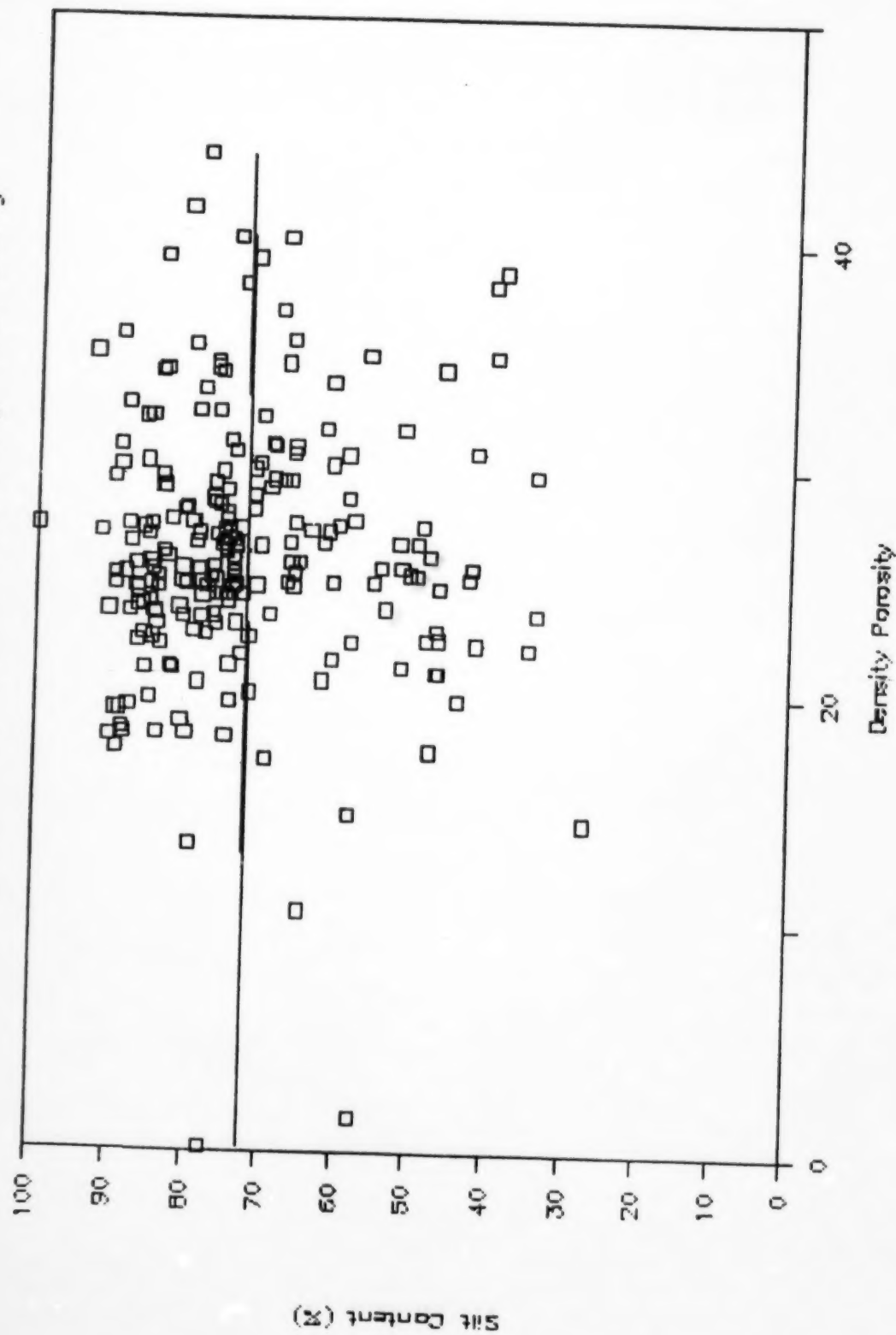
Constant	72.39346	
Std Err of Y Est	14.05090	
R Squared	0.00003	R Value 0.005018
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	0.01218	
Std Err of Coef.	0.16470	Y=0.012*X+72.393

Regression Analysis Output for
Log of Silt Content (Log %) vs Density Porosity

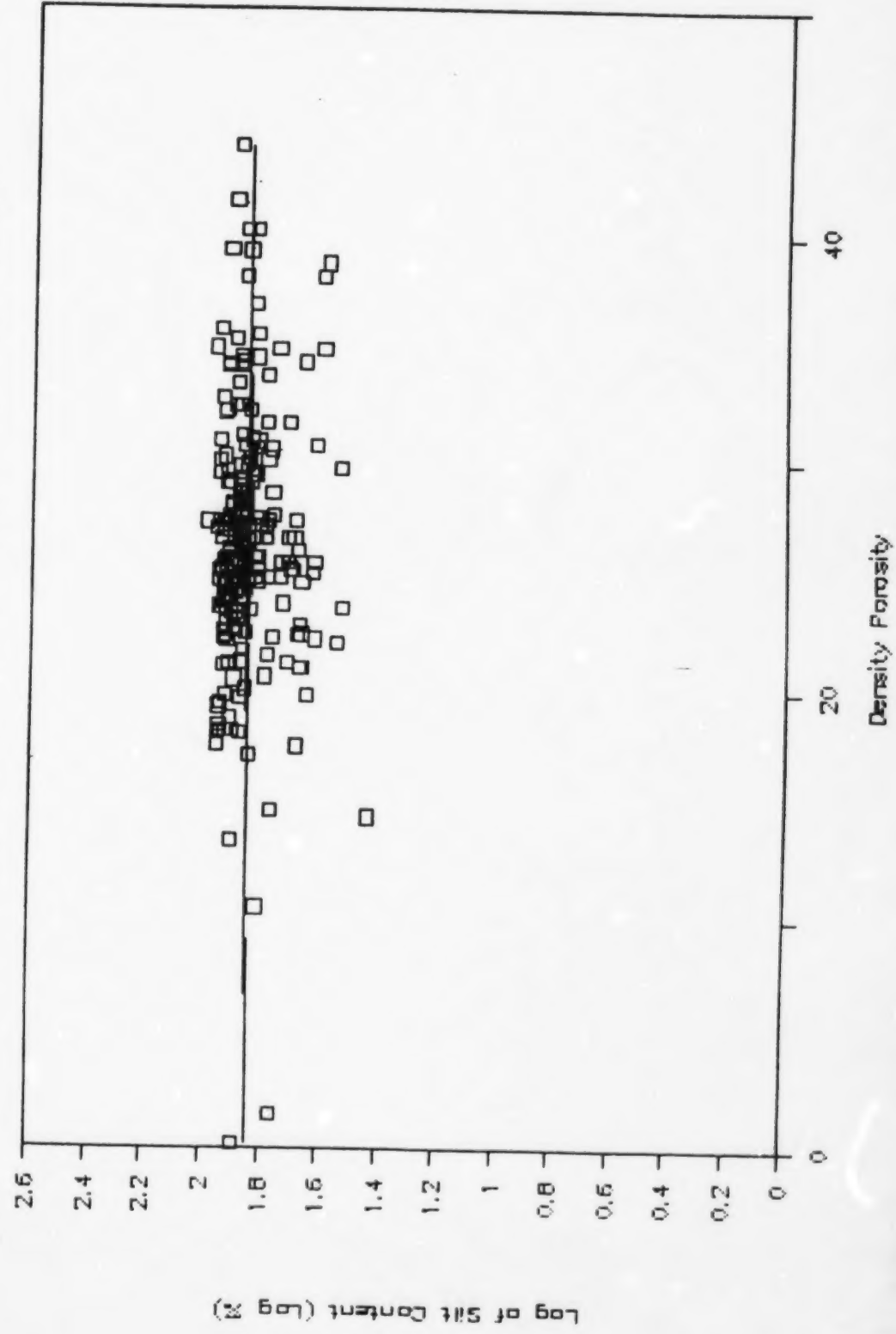
Regression Output:

Constant	1.84356	
Std Err of Y Est	0.09801	
R Squared	0.00034	R Value 0.018541
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	0.00031	
Std Err of Coef.	0.00115	Y=0.0003*X+1.844

Silt Content (%) vs Density Porosity



Log Silt Content vs Density Porosity



Regression Analysis Output for
Sand Content (%) vs Resistivity Log

Regression Output:

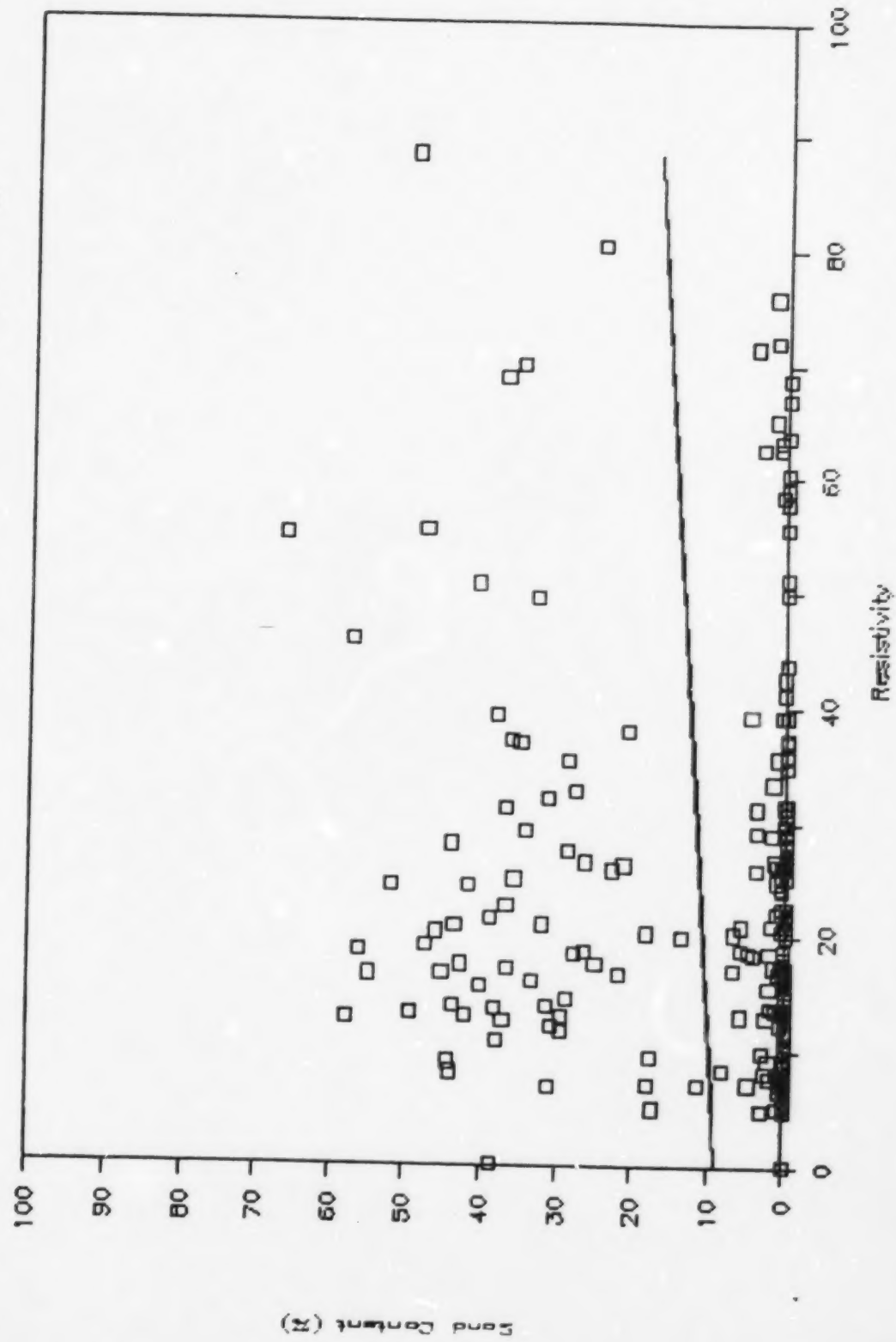
Constant	8.896		
Std Err of Y Est	17.116		
R Squared	0.010	R Value	0.100
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.098		
Std Err of Coef.	0.066		$Y=0.098 \times X + 8.896$

Regression Analysis Output for
Log of Sand Content (Log %) vs Resistivity Log

Regression Output:

Constant	0.415		
Std Err of Y Est	0.754		
R Squared	0.002	R Value	0.049
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.002		
Std Err of Coef.	0.003		$Y=0.002 \times X + 0.415$

Sand Content (%) vs Resistivity Log



Log Sand Content (%) vs Resistivity Log



Regression Analysis Output for
Sand Content (%) vs Neutron Porosity Log

Regression Output:

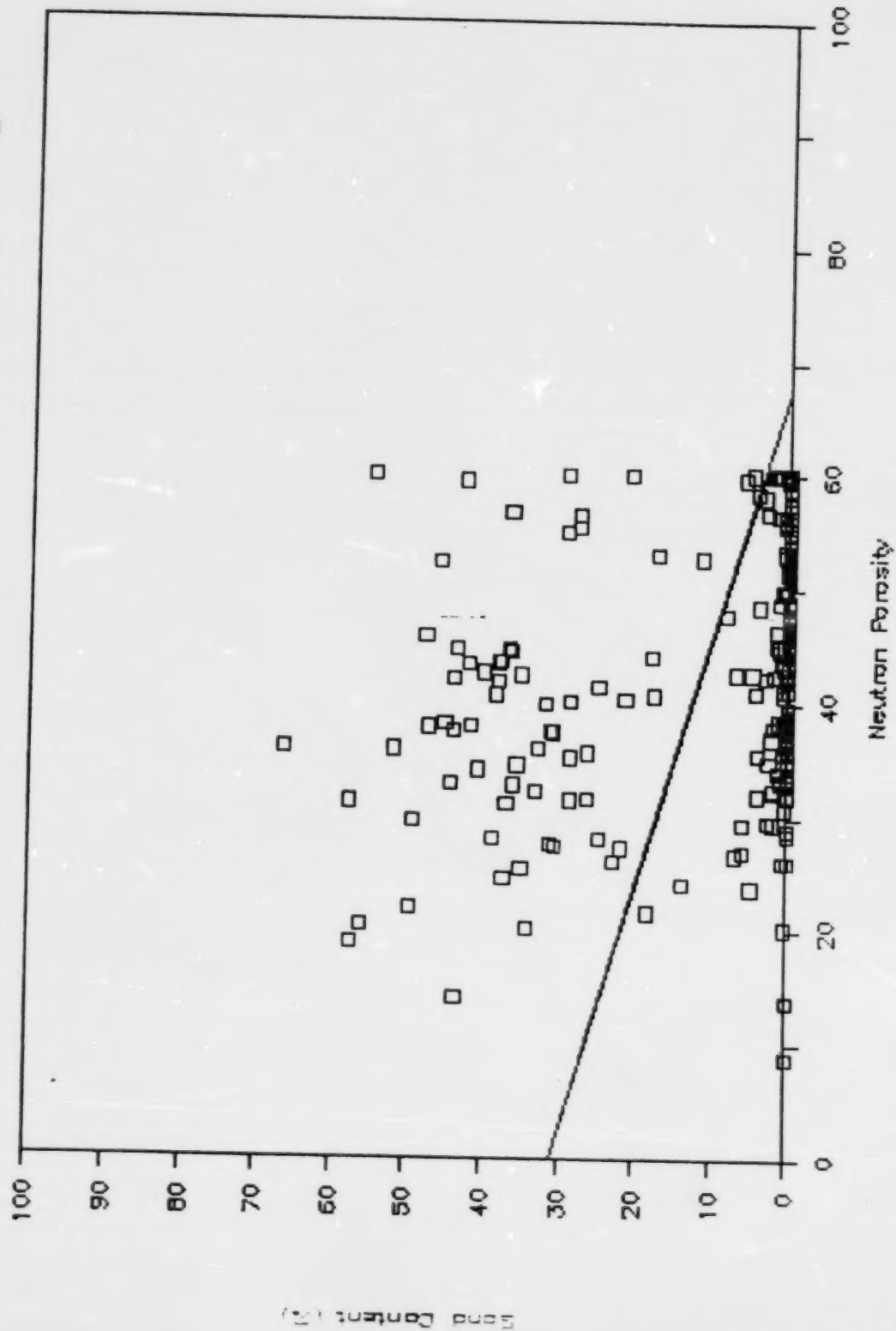
Constant	30.831		
Std Err of Y Est	16.405		
R Squared	0.090	R Value	0.301
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	-0.456		
Std Err of Coef.	0.098		$Y = -0.456X + 30.831$

Regression Analysis Output for
Log of Sand Content (Log %) vs Neutron Porosity Log

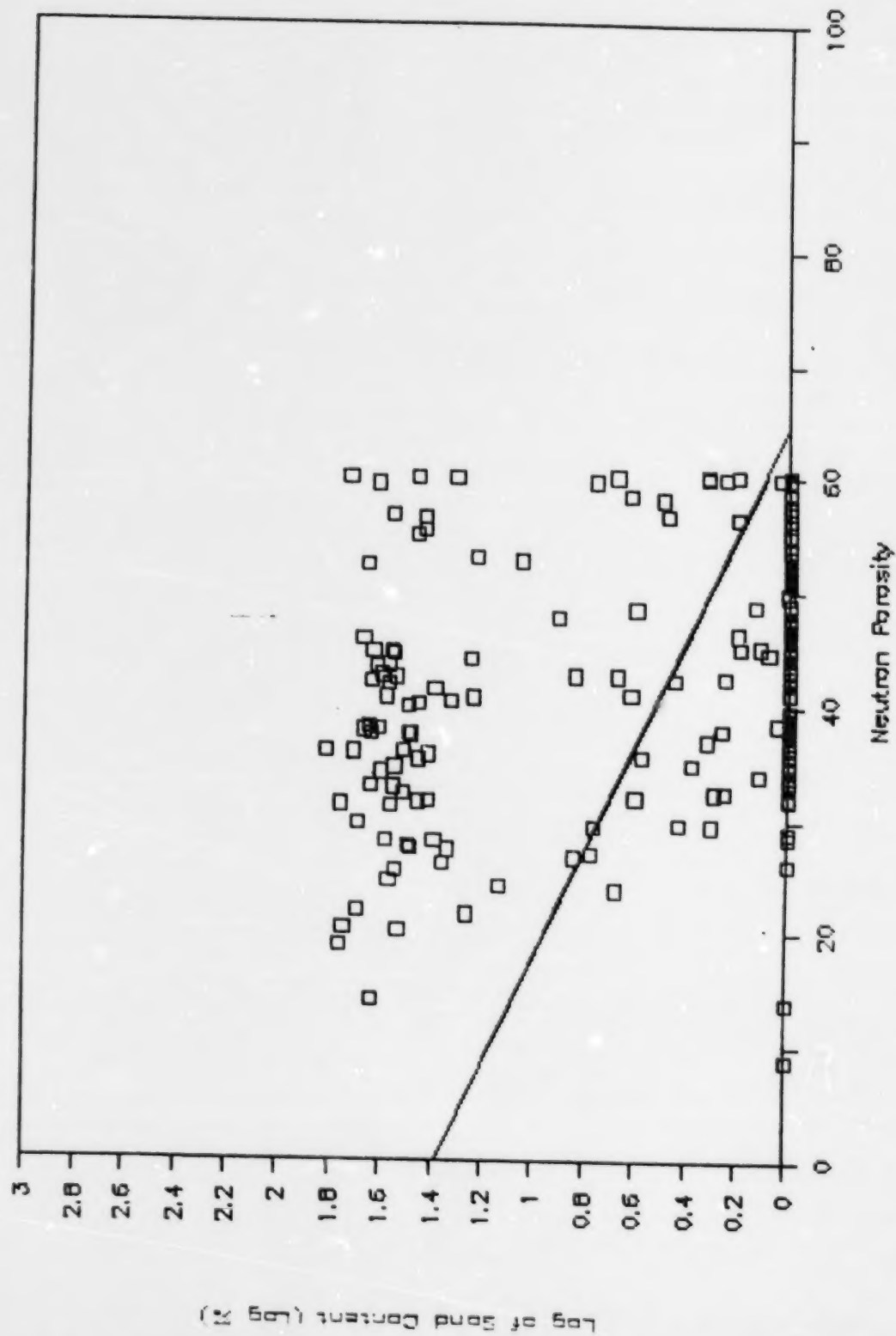
Regression Output:

Constant	1.381		
Std Err of Y Est	0.715		
R Squared	0.103	R Value	0.320
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	-0.021		
Std Err of Coef.	0.004		$Y = -0.021X + 1.381$

Sand Content(%) vs Neutron Porosity Log



Sand Content vs Neutron Porosity Log



Regression Analysis Output for
Sand Content (%) vs Density Porosity

Regression Output:

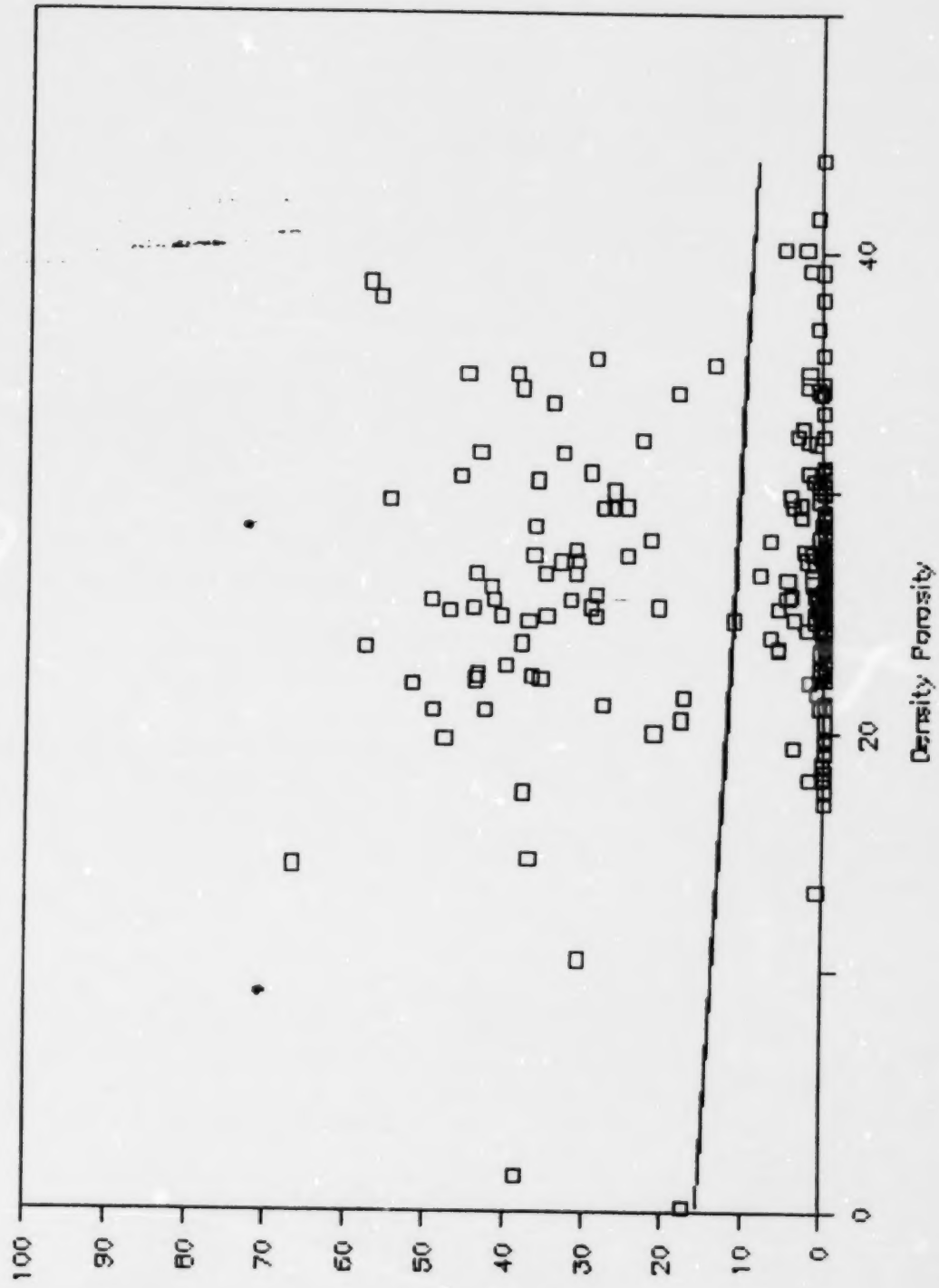
Constant	15.447	
Std Err of Y Est	17.176	
R Squared	0.003	R Value 0.054357
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.161	
Std Err of Coef.	0.201	Y=-0.161*X+15.447

Regression Analysis Output for
Log of Sand Content (Log %) vs Density Porosity

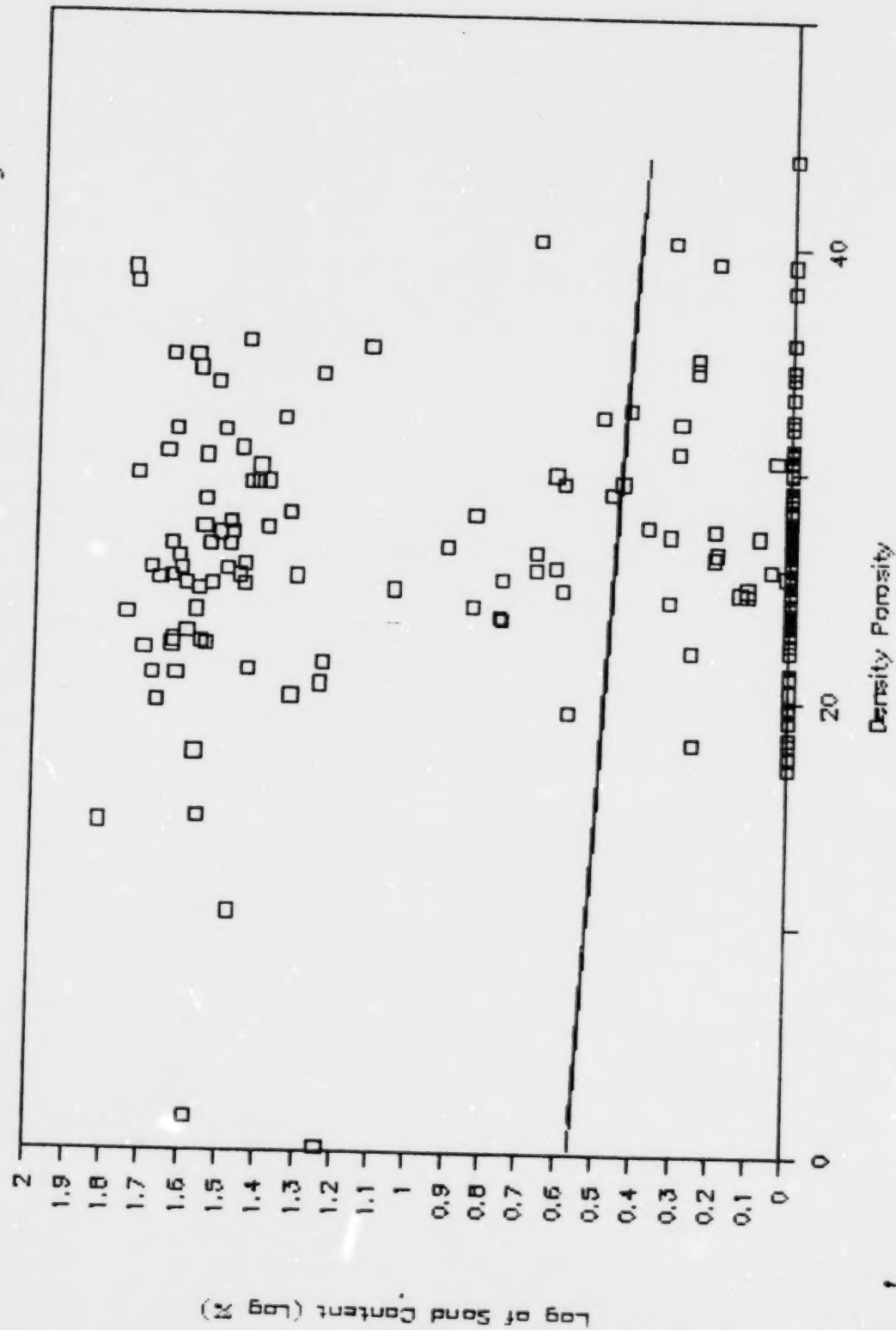
Regression Output:

Constant	0.562	
Std Err of Y Est	0.754	
R Squared	0.001	R Value 0.028595
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.004	
Std Err of Coef.	0.009	Y=-0.004*X+0.562

Sand Content (%) vs Density Porosity



Log Sand Content vs Density Porosity



Regression Analysis Output for
Sand Content (%) vs Gamma Log

Regression Output:

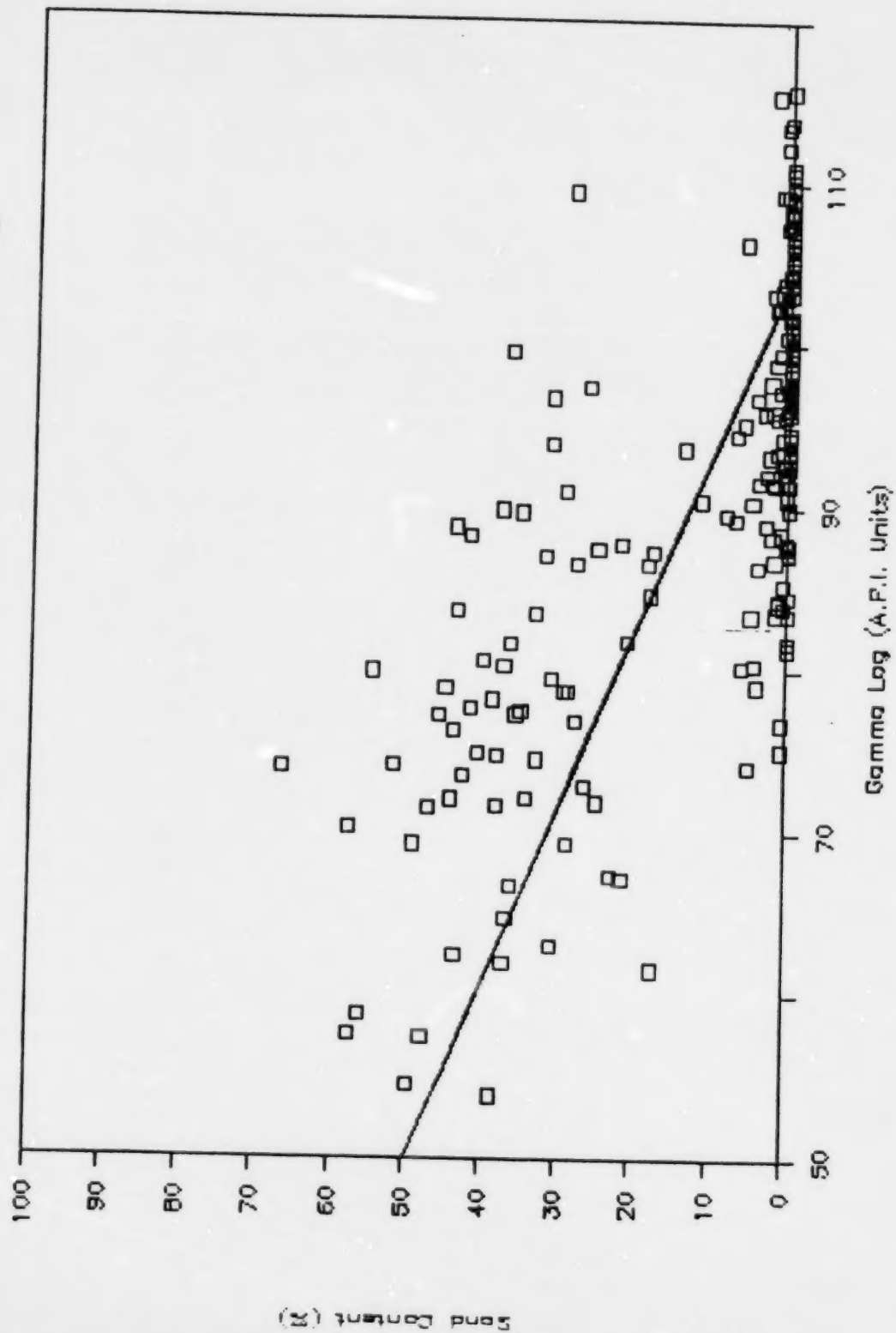
Constant	95.681	
Std Err of Y Est	11.925	
R Squared	0.519	R Value 0.720715
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.920	
Std Err of Coef.	0.060	Y=-0.920*X+95.681

Regression Analysis Output for
Log of Sand Content (Log %) vs Gamma Log

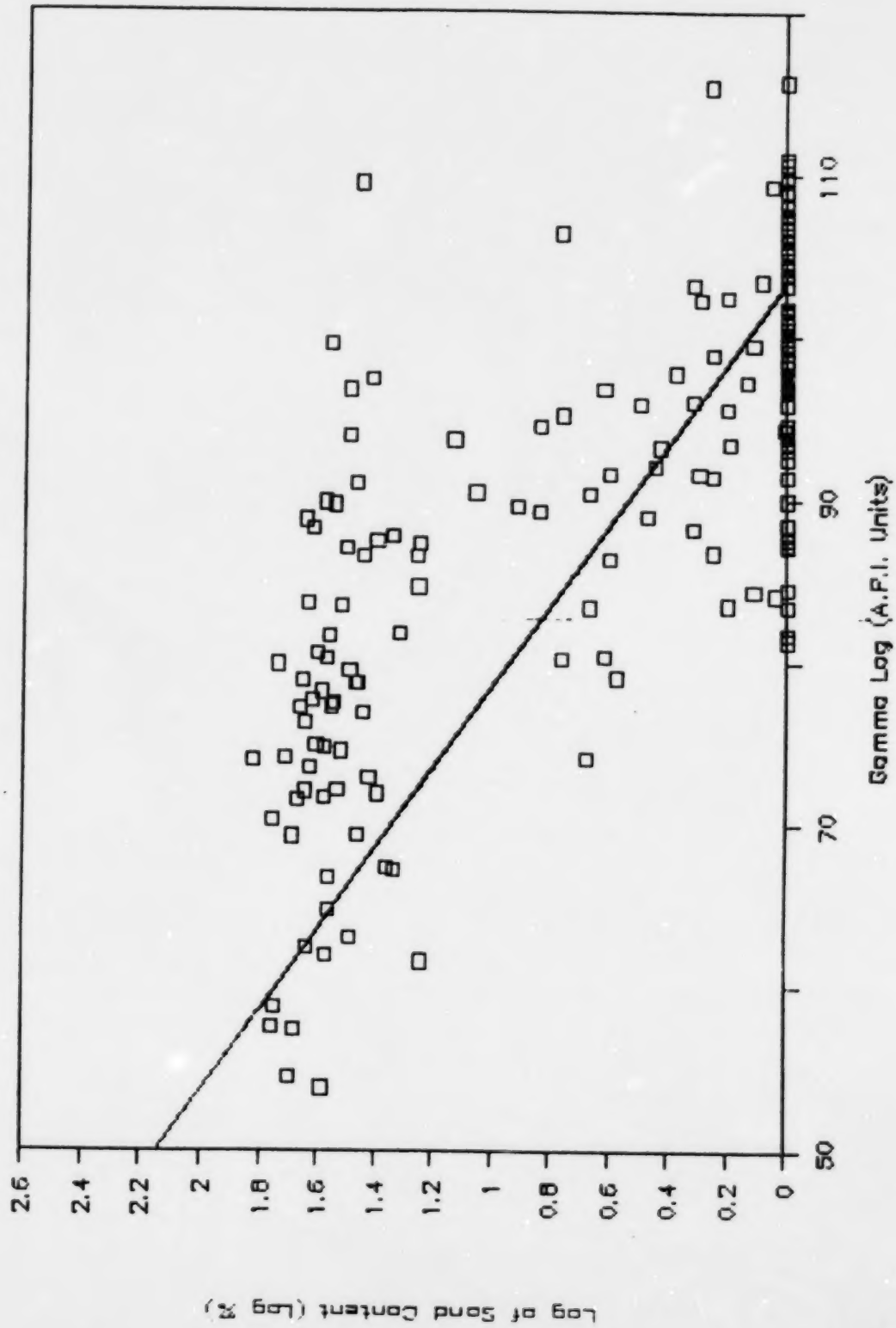
Regression Output:

Constant	4.150	
Std Err of Y Est	0.526	
R Squared	0.514	R Value 0.717
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.040	
Std Err of Coef.	0.003	Y=-0.040*X+4.150

Sand Content (%) vs Gamma Log



Log of Sand Content (Log%) vs Gamma Log



Regression Analysis Output for
Gradation Curve Slope vs Density Porosity

Regression Output:

Constant	-1.223		
Std Err of Y Est	0.237		
R Squared	0.000	R Value	0.005
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	-0.00021		
Std Err of Coef.	0.00278		

$Y = -0.0002 \times X - 1.223$

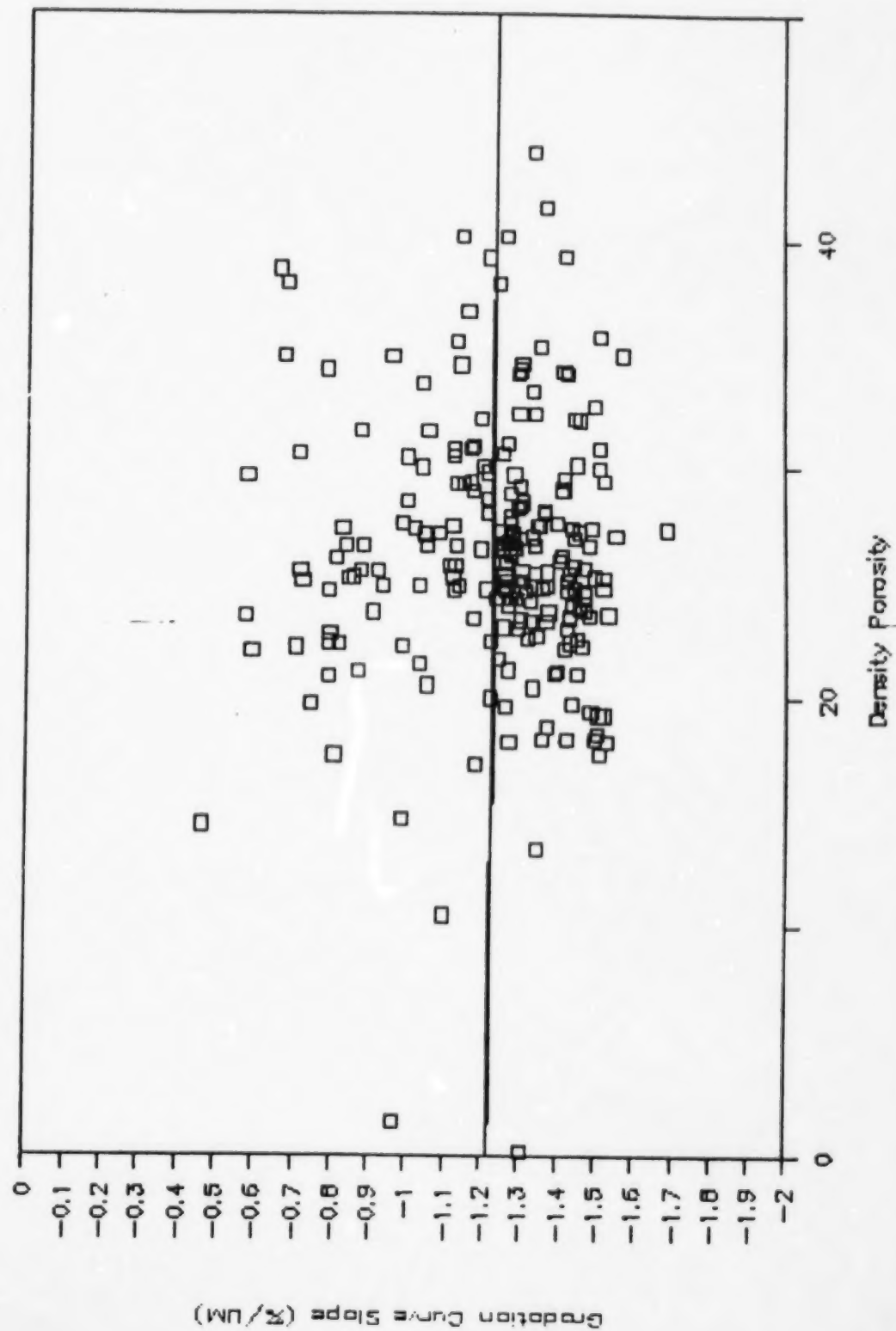
Regression Analysis Output for
Log of Gradation Curve Slope vs Density Porosity Log

Regression Output:

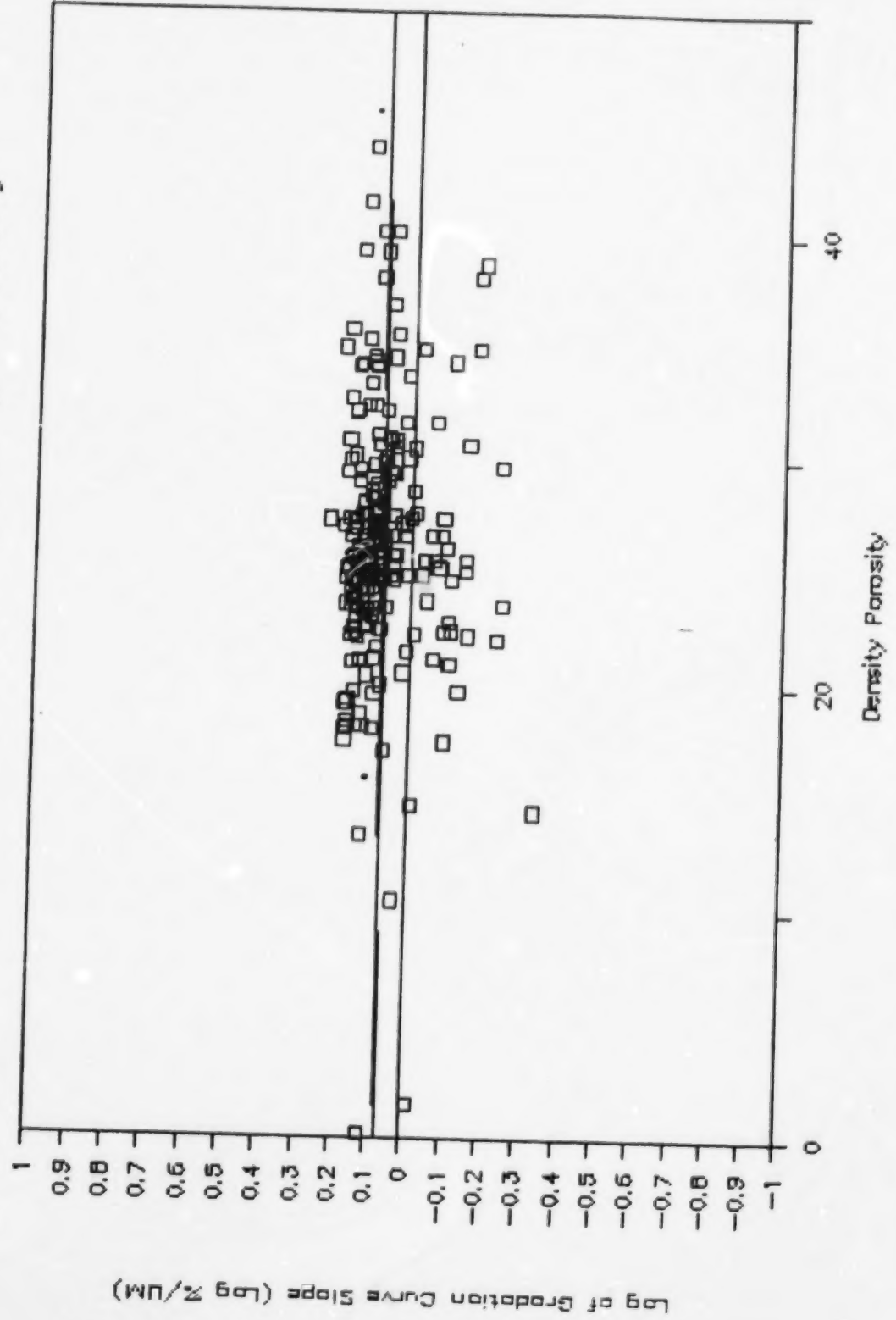
Constant	0.07124		
Std Err of Y Est	0.09801		
R Squared	0.00034	R Value	0.018541225
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.00031		
Std Err of Coef.	0.00115		

$Y = 0.0003 \times X + 0.071$

Curve Slope (%/UM) vs Density Porosity



Log Curve Slope vs Density Porosity



Regression Analysis Output for
Gradation Curve Slope vs Gamma Log

Regression Output:

Constant	-0.230		
Std Err of Y Est	0.187		
R Squared	0.381	R Value	0.617
No. of Observations	219.000		
Degrees of Freedom	217.000		

X Coefficient(s) -0.01087
Std Err of Coef. 0.00094

$$Y = -0.011X - 0.230$$

Regression Analysis Output for
Log of Gradation Curve Slope vs Gamma Log

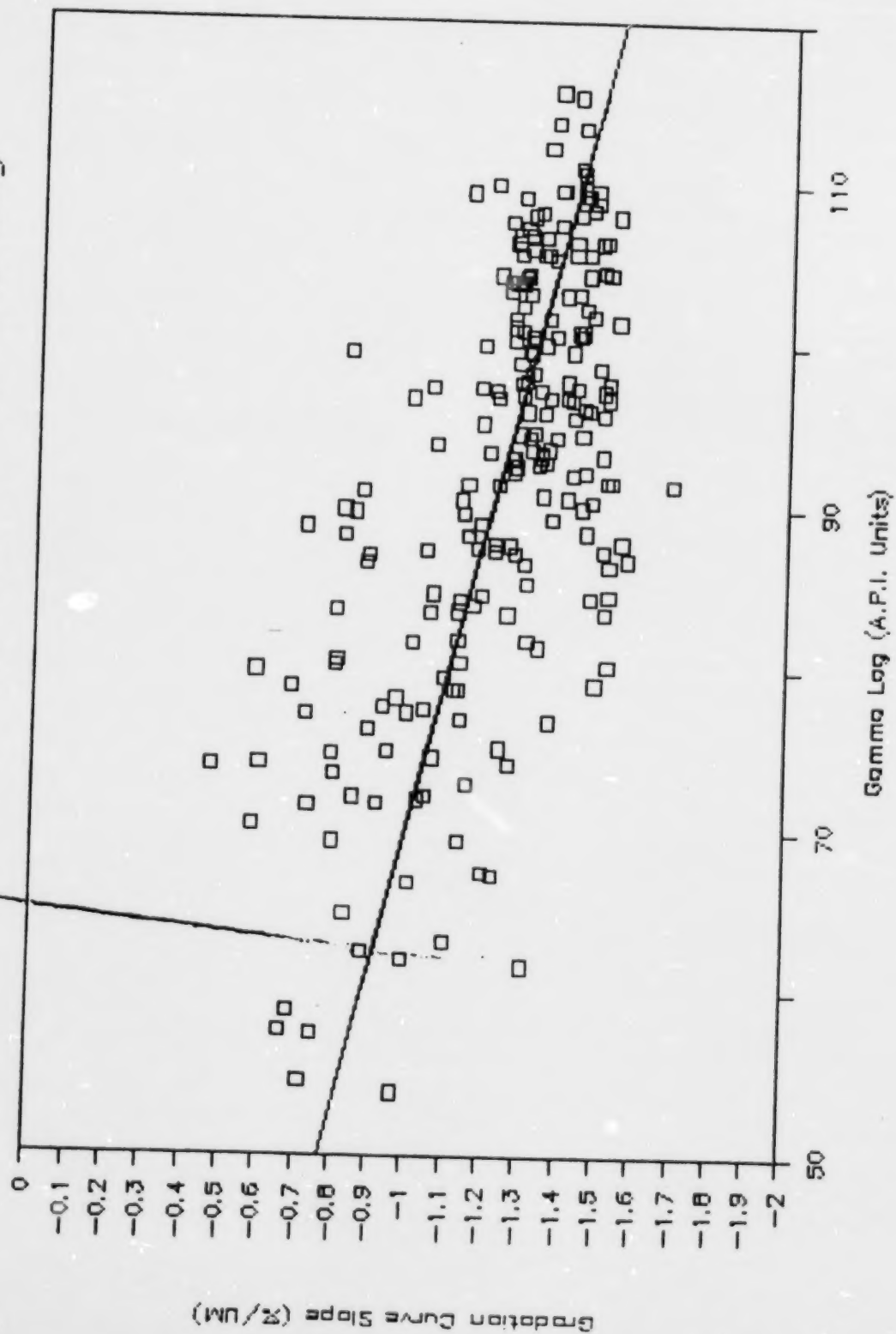
Regression Output:

Constant	-0.330		
Std Err of Y Est	0.077		
R Squared	0.377	R Value	0.613794865
No. of Observations	219.000		
Degrees of Freedom	217.000		

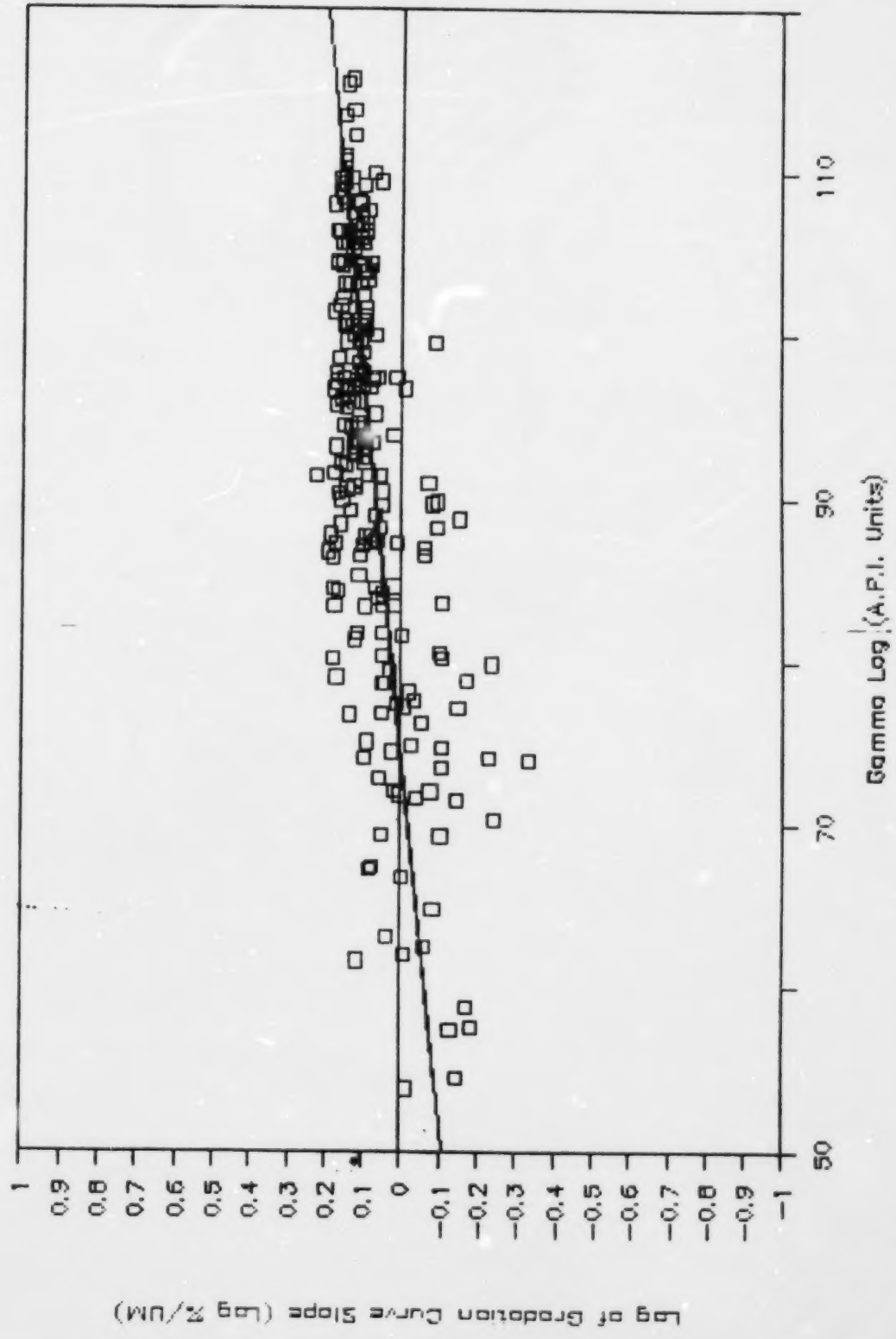
X Coefficient(s) 0.00446
Std Err of Coef. 0.00039

$$Y = 0.004X - 0.330$$

Gradation Curve Slope vs Gamma Log



Log Gradation Curve Slope vs Gamma Log



Regression Analysis Output for
Gradation Curve Slope vs Neutron Porosity Log

Regression Output:

Constant	-1.143		
Std Err of Y Est	0.236		
R Squared	0.009	R Value	0.094
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	-0.00197		
Std Err of Coef.	0.00142		

$Y = -0.002 \times X - 1.143$

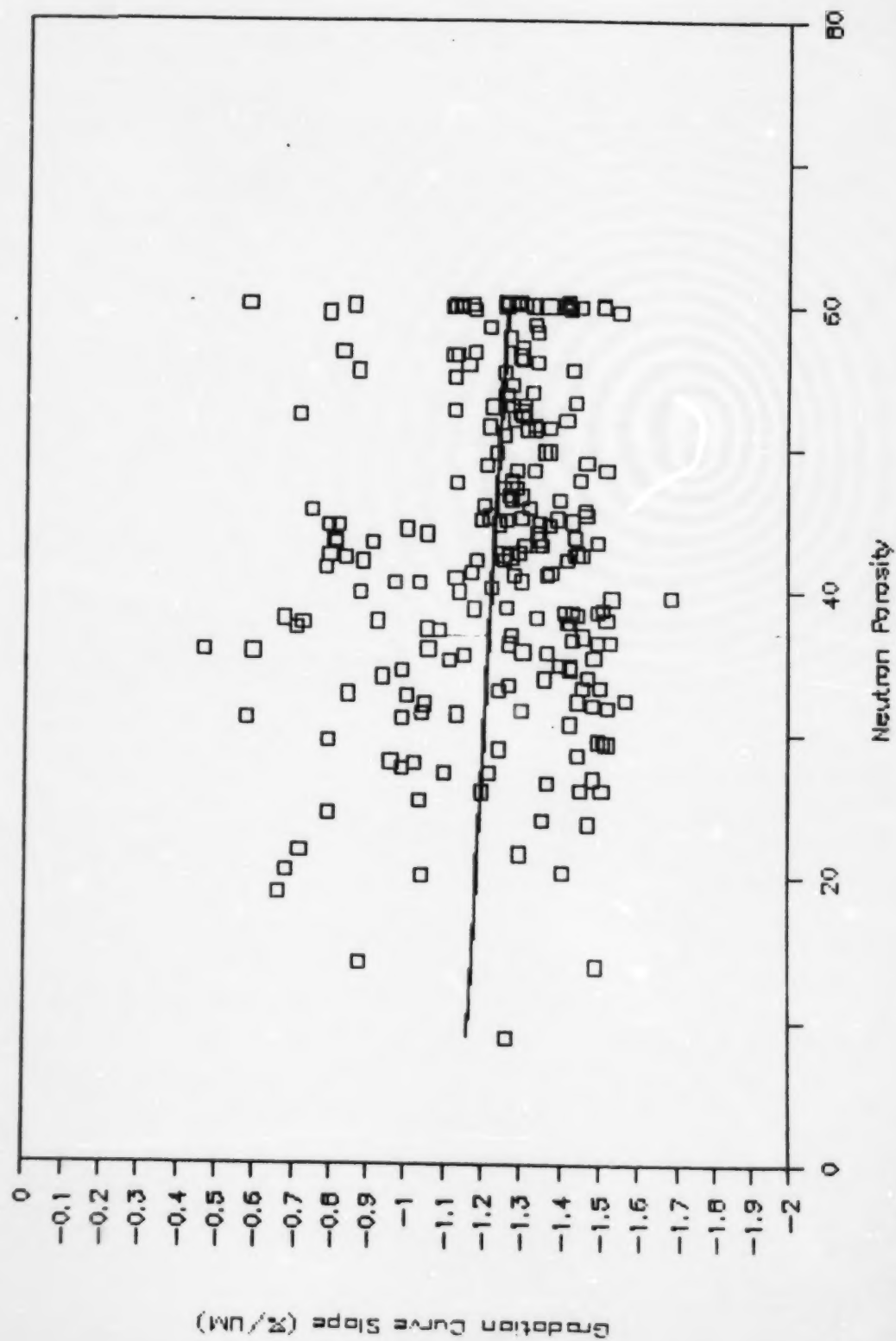
Regression Analysis Output for
Log of Gradation Curve Slope vs Neutron Porosity Log

Regression Output:

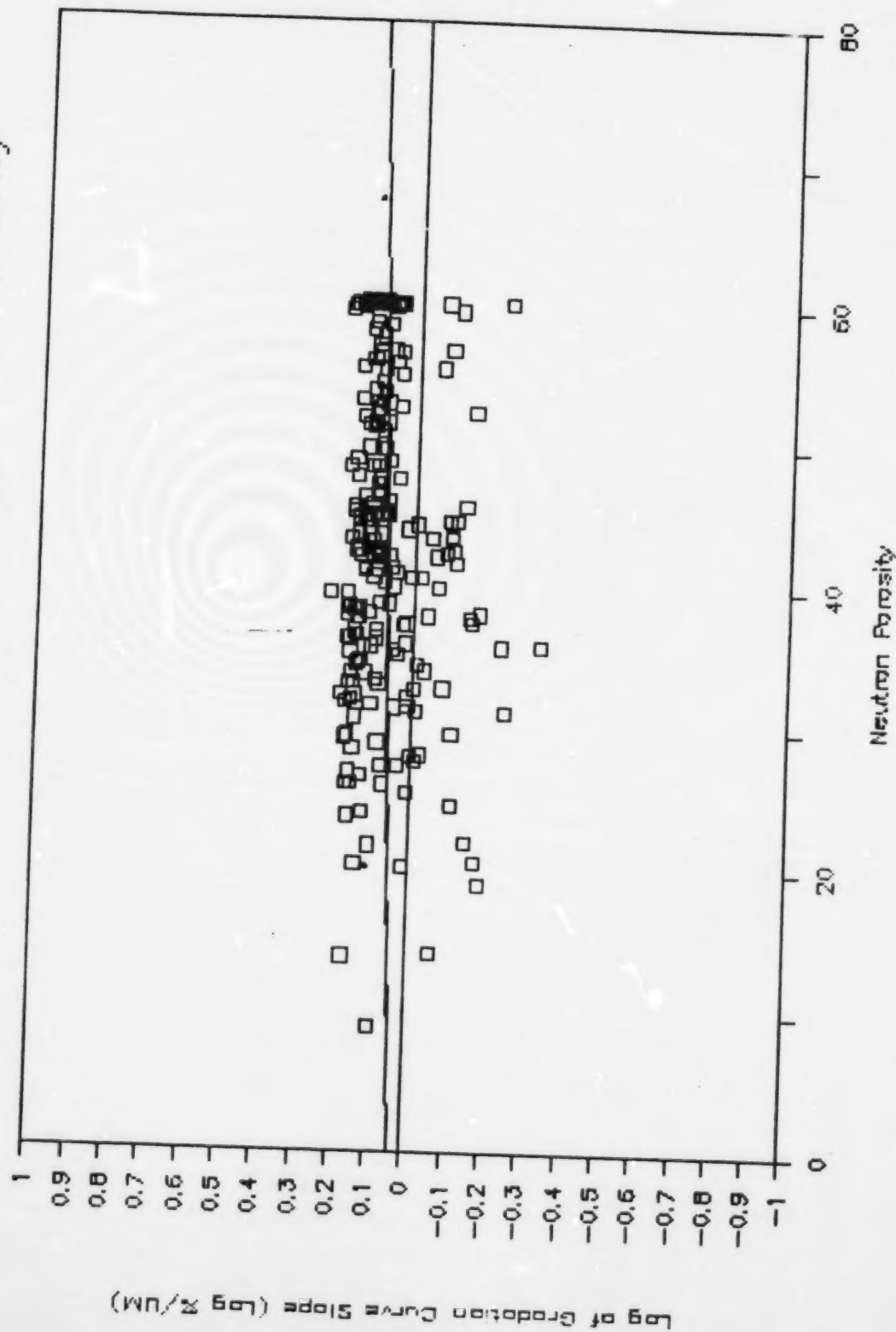
Constant	0.036		
Std Err of Y Est	0.097		
R Squared	0.014	R Value	0.116572583
No. of Observations	219.000		
Degrees of Freedom	217.000		
X Coefficient(s)	0.00101		
Std Err of Coef.	0.00058		

$Y = 0.001 \times X + 0.036$

Curve Slope (%/UM) vs Neutron Porosity



Log of Curve Slope vs Neutron Porosity



Regression Analysis Output for
Gradation Curve Slope vs Resistivity Log

Regression Output:

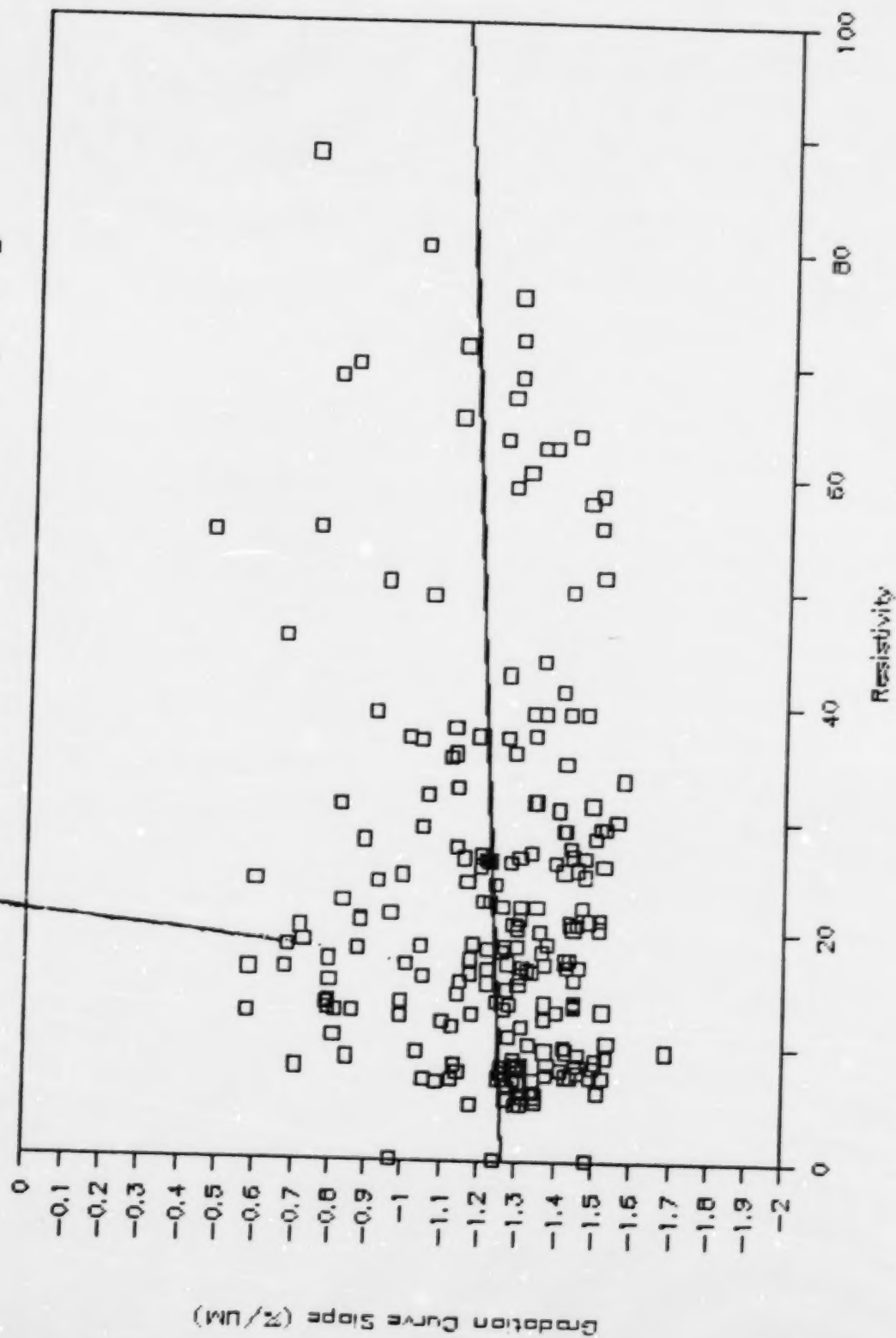
Constant	-1.263	
Std Err of Y Est	0.236	
R Squared	0.012	R Value 0.109073776
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	0.00148	
Std Err of Coef.	0.00091	Y=0.001*X-1.263

Regression Analysis Output for
Log of Gradation Curve Slope vs Resistivity Log

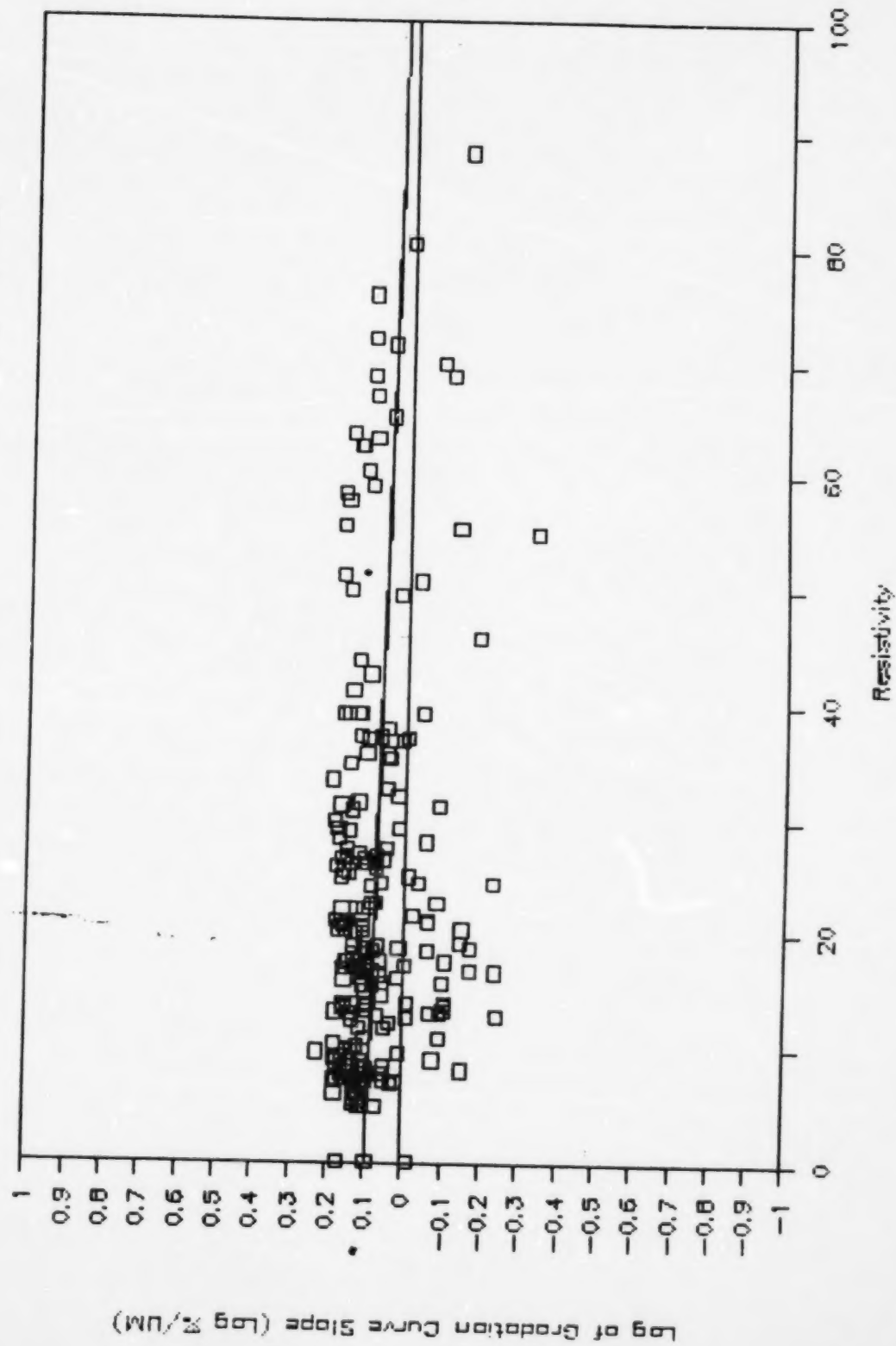
Regression Output:

Constant	0.094	
Std Err of Y Est	0.097	
R Squared	0.013	R Value 0.113605108
No. of Observations	219.000	
Degrees of Freedom	217.000	
X Coefficient(s)	-0.00064	
Std Err of Coef.	0.00038	Y=-0.0006*X+0.094

Slope (%/UM) vs Resistivity Log



Log Curve Slope vs Resistivity Log



APPENDIX V
HYDROGEOLOGICAL COAL CORRELATIONS

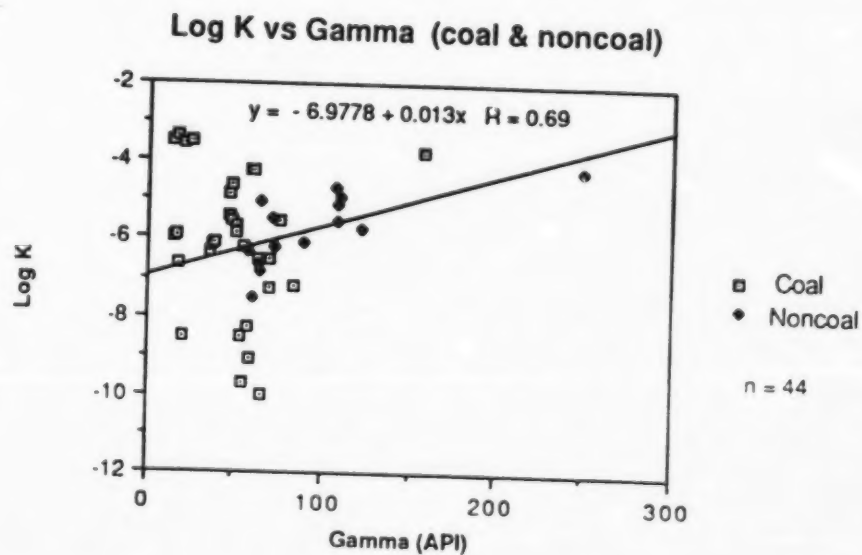
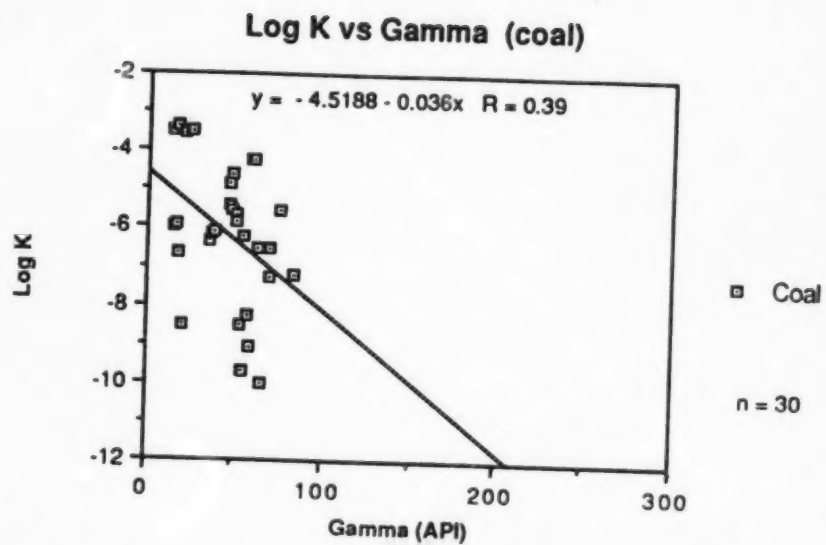
Detailed Procedure of Data Search and Analysis Followed For Hydrogeologic Correlations

The collection, organization and preparation of data to be used for correlations proved to be more of a difficult and time consuming task than originally anticipated. Several steps had to be carried out before the actual correlations could even be made. The list below shows the analytical process followed for the data workup.

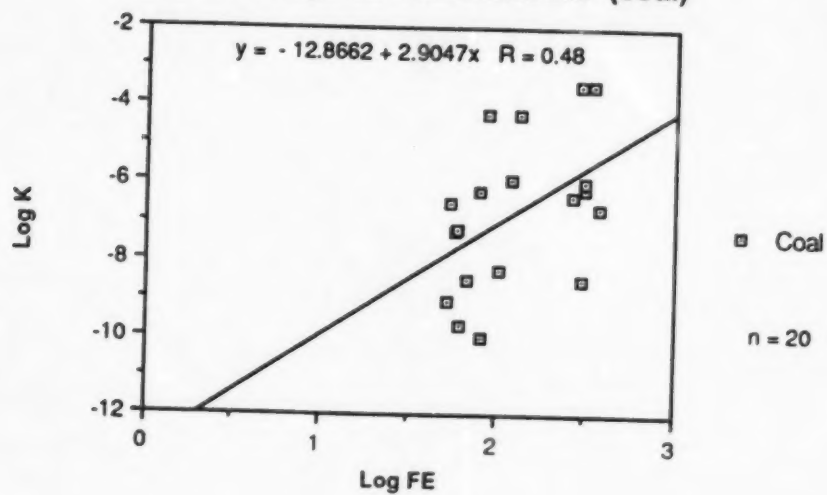
- parameters of interest identified.
- a search of existing hydrogeologic data from ARC projects checked for potential use (PHRP and Highwall Stability Studies).
- data set narrowed down to records with geophysical log data.
- geophysical log data retrieval was first attempted from magnetic tape.
- this proved unsuccessful because digital log data were in BPB field format on cassette tapes which could not be easily read into ARC computers.
- preliminary attempts at reformatting data proved too costly and time consuming (~\$50 per hole).
- for analysis, decided to proceed with a smaller data set by digitizing the hard paper copy logs for only a few holes.
- decided the target for first correlations attempt should concentrate on a single, easily identifiable lithology - coal.
- used ARC's log analysis system, Logmate on HP desktop computer to digitize paper logs.
- digitized a total of 70 logs from 14 holes at an average depth of 50m.
- 10cm increment used for producing digital value.
- digital log data were tabulated and formatted for transfer to the VAX computer.
- log data were then transferred from VAX to a Macintosh microcomputer where first analysis were carried out.
- in the Macintosh, log data was reformatted and edited to select the desired depth interval (chose log values from the exact depth interval that corresponded to depth of piezometer screen).
- log data was then dumped into spread sheet program (Microsoft Excel) for organization and manipulation.
- in Excel; log values averaged over same depth as screen intervals, hydraulic conductivity (K) values entered, calculations made to some

values to give preferred new value (velocity from sonic, density in gm/cc from density log in sdu, linearize the values of FE log and K by taking the log of those values)(Table 1).

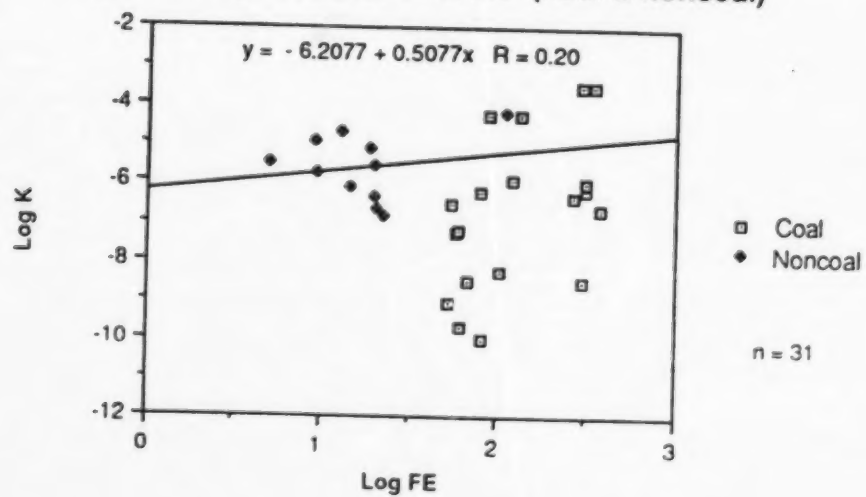
- after edits of data finalized, data dumped into graphics presentation software program (Cricket Graph) for plotting on x/y scatter graphs.
- crossplots were made for K and the different geophysical log types.
- selected data was transferred back into VAX for analysis on SAS program to correlate K with combined sets of geophysical log values.



Log K vs Log Focussed Electric (coal)

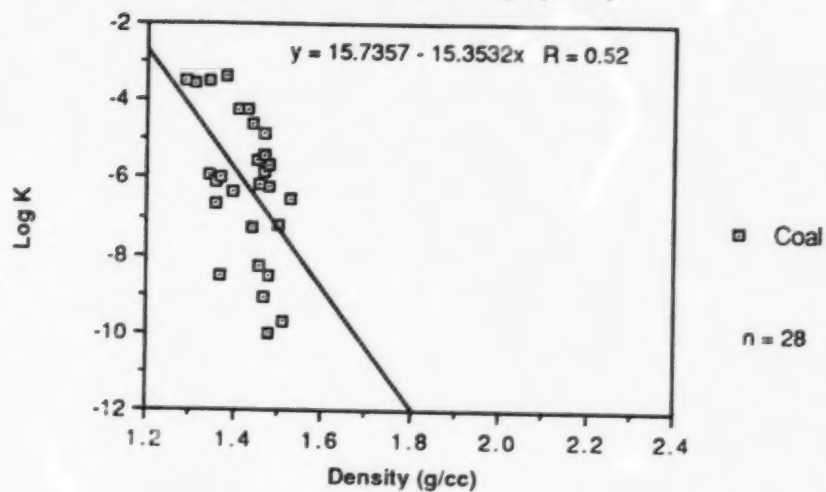


Log K vs Log Focussed Electric (coal & noncoal)

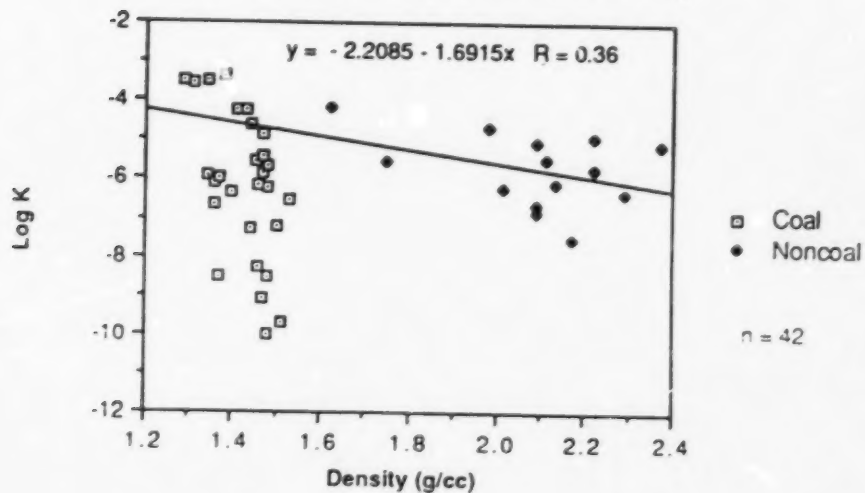


X

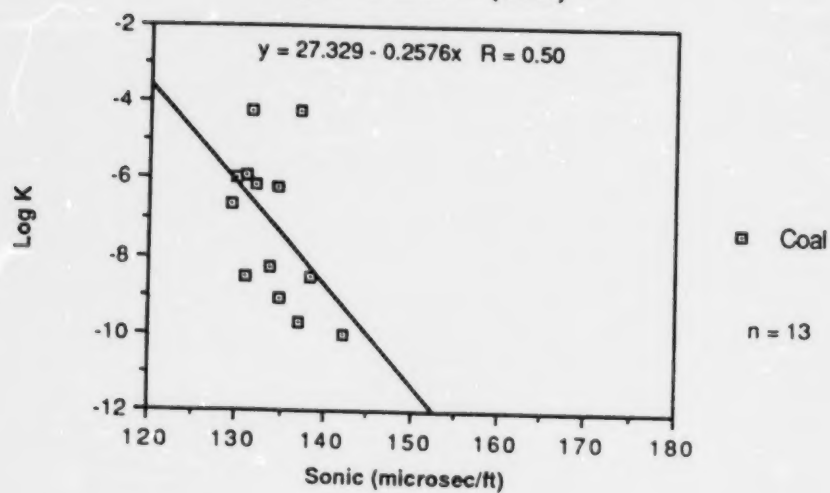
Log K vs Bulk Density (coal)



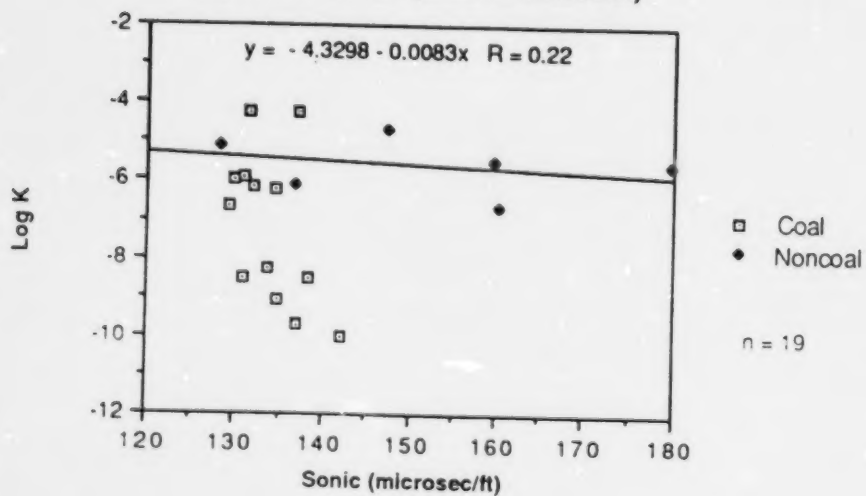
Log K vs Bulk Density (coal & noncoal)



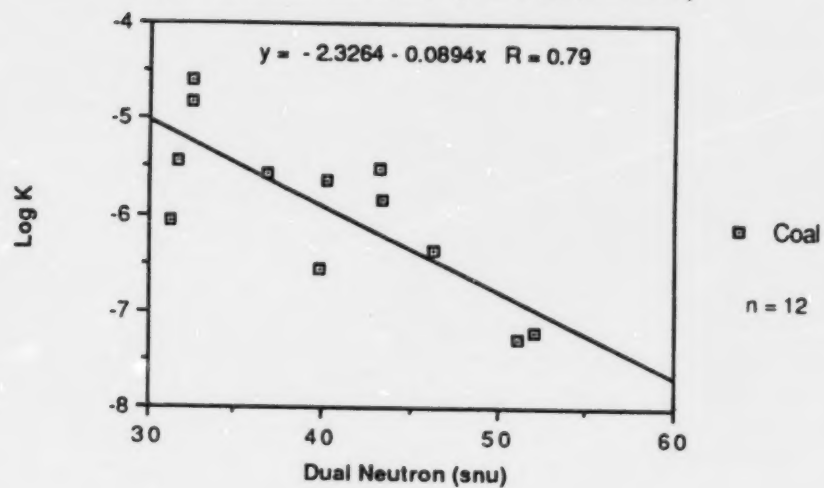
Log K vs Sonic (coal)



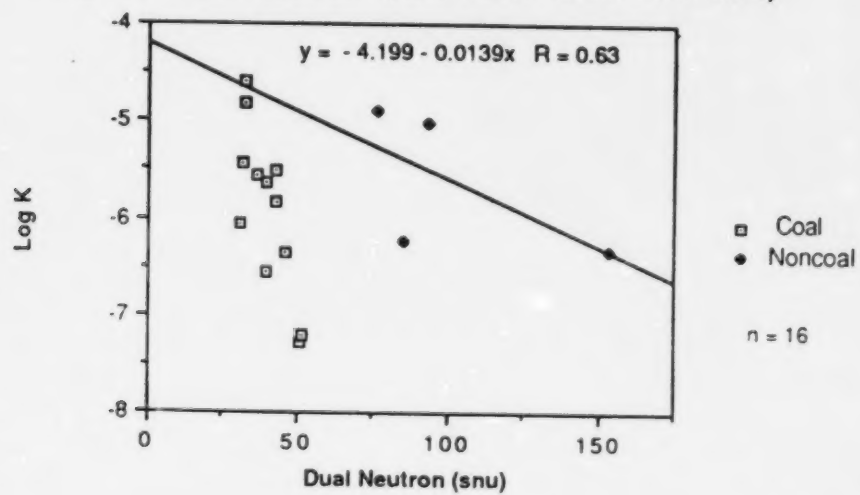
Log K vs Sonic (coal & noncoal)



Log K vs Dual Neutron (ARC data - coal)



Log K vs Dual Neutron (ARC data - coal & noncoal)



Log K vs Dual Neutron (TAU data - coal)

